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# EFFECTS OF TRAFFIC PRIOR TO COOLING ON RUT DEVELOPMENT IN ASPHALT MIXES

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# EFFECTS OF TRAFFIC PRIOR TO COOLING ON RUT DEVELOPMENT IN ASPHALT MIXES

by

R. Yacyshyn

K. K. Tam

D. F. Lynch

Bituminous Section

Engineering Materials Office

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# TECHNICAL REPORT DOCUMENTATION PAGE

## EFFECTS OF TRAFFIC PRIOR TO COOLING ON RUT DEVELOPMENT IN ASPHALT MIXES


Authors: R. YACYSHYN, K.K. TAM, D.F. LYNCH



Abstract:

The practice of prematurely allowing traffic on hot mix surfaces after construction has been suspected of initiating and accelerating pavement rutting. This laboratory study examines the rutting of a variety of Ontario mix types in conditions similar to the above practice where elevated mix temperatures make the pavement most prone to traffic compaction and rutting. Samples were tested at various initial temperatures representing different temperatures for the opening of pavements to traffic. A prescribed method using a wheel tracking machine in a laboratory was used to determine their temperature susceptibility to rutting.

The results indicate that while the severity of the rutting is a characteristic of individual mixes, the degree of initial rutting is directly affected by the pavement temperature at which traffic travel is permitted. Although stable mixes currently used were found to be least temperature susceptible, raising the initial test temperature from 60°C to 100°C was found to increase the rut depth of all mixes by an average of 160%. Most of the rut depth is produced within the early stages of testing when the mix temperatures are still high. This highlights the importance of requiring a cooling period prior to opening to traffic. In practice, this is achieved in the field by allowing constructed pavement temperatures, especially in high traffic volume locations, to drop to 60°C before subjecting the freshly laid mixes to the stresses of traffic compaction.

Abrégé:

On croit que la pratique consistant à laisser prématurément les véhicules rouler sur les surfaces recouvertes de mélange à chaud après les travaux de construction cause et accélère l'orniérage de la chaussée. La présente étude de laboratoire porte sur l'orniérage de divers types de mélanges ontariens dans des conditions similaires à celles décrites précédemment, soit lorsque la température élevée du mélange rend la chaussée davantage susceptible au compactage et à l'orniérage par la circulation. Des échantillons one été testés à des températures initiales équivalant à la température de la chaussée lors de l'ouverture à la circulation. On a utilisé une methode prescrite faisant appel à un appareil reproduisant les traces laissées par les roues pour déterminer la sensibilité de la chaussée à l'orniérage, à diverses températures.

Selon les résultats obtenus, bien que l'ampleur de l'orniérage dépende du type de mélange, le degré d'orniérage initial est directement proportionnel à la température de la chaussée lorsque la voie est réouverte à la circulation. Bien que l'on ait constaté que les mélanges stables utilisés actuellement sont les moins influencés par la température, on a également observé que si la température du mélange lors du test initial passait de 60 °C à 100 °C, le degré d'orniérage de tous les mélanges augmentait en moyenne de 160 pour 100. La majeure partie de l'orniérage survient au début du test, lorsque la température du mélange est élevée. Cette observation témoigne de l'importance de prévoir une période de refroidissement avant d'ouvrir la chaussée à la circulation. Dans la pratique et surtout dans les endroits où la circulation est très dense, on laisse la chaussée se refroidir jusqu'à ce que sa température atteigne 60°C avant de soumettre la nouvelle couche bitumineuse au compactage par la circulation.



Keywords: Rutting, deformation, permanent strain, flexible pavements, asphaltic concrete, pavement temperature, laboratory testing, wheel-tracking machine.

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## 1. INTRODUCTION

In recent years greater attention has been given to the rutting of asphalt pavements, a problem which contributes to structural as well as functional pavement failure of highways. Without rutting, motorists would benefit from better steering control and less danger from hydroplaning in rain or skidding in icy conditions. The costly rehabilitation of highways due to this distress mode has encouraged the highway industry to determine the causes and apply preventive measures.

Two factors frequently mentioned in literature in association with rutting are heavy loading and high tire pressures. The effects of loading with pavement depth have been well documented (1). In the transportation of goods up to or beyond the maximum weight allowed by regulation, overland carriers can in some instances reduce the number of runs and consequently save a portion of their fuel costs. Also, reduced rolling resistance from the use of radial rather than bias ply tires can result in further energy savings. A recent truck-tire pressure survey by the Ministry of Transportation of Ontario (2) has shown the average pressure of radial tires to be 740 kPa (107 psi), almost 50% higher than the average pressure of bias ply tires.

In another study, by Marshek et al (3), it was found that tire contact pressure was much higher than previously believed under some portions of the tire tread; this further substantiates the suggestion that rutting is associated with tire pressure. Over or underinflation may be producing much higher tensile stresses at the bottom of a surfacing layer than previously believed, stresses that present pavements have not been designed for.

Accentuating the above factors is the traffic increase which, on some sections of Hwy. 401, has risen almost 50% (4) over the past ten years according to the Annual Average Daily Traffic (A.A.D.T.) figures. The

increased volume of traffic inhibits the speed of paving operations nowadays and forces the opening of newly surfaced roads to traffic earlier, before hot mix temperatures have subsided to acceptable levels for trafficking. Therefore, determining the extent of the temperature role on rutting under these conditions may provide insight on how to effectively reduce the rutting damage.

## 2. PURPOSE AND SCOPE

The purpose of this study is to evaluate the effects of traffic on pavement rutting immediately after construction and during the cooling of asphalt mixes to ambient temperatures. The study is performed in the laboratory using the Wheel Tracking Machine (W.T.M.) shown in Figure 1 and takes into account:

(a) different finishing construction temperatures ranging from 60 to 100°C with 60°C assumed to be the surface temperature of the underlying pavement.

(b) a variety of mix types commonly used by the Ministry, i.e., H.L.-1, H.L.-3, H.L.-3 R.H.M., H.L.-4, H.L.-8, D.F.C., modified D.F.C. and an O.F.C.

(c) the different degrees of rutting as produced by the W.T.M. on samples from the field as well as on those manufactured in the laboratory.

## 3. MIX SELECTION

In order to cover the above points in this study, a comprehensive range of Ontario aggregates and mix types were considered. On the presumption that they would be monitored for rutting in the future, ongoing as well as past contract mixes with an adequate supply of aggregates were selected. The nature of the 11 mixes, which includes one H.L.-1, two H.L.-3's, three H.L.-4's, two H.L-8's, two D.F.C's and one O.F.C., is fully described in Table 1.

For comparison, field samples from previous rutting investigations were also tested by the W.T.M. Three of these are from Highway 401 and one comes from Bloomington Road. They consist of portions of the actual pavements containing lifts of H.L.-3 over H.L.-8 for Bloomington Road and H.L.-1 over H.L.-4 for Highway 401.

## 4. MATERIAL QUALITY

Petrographic Number (P.N.) and percent crushed have long been used as indices of aggregate quality in the design of mixes. For this project, the mix aggregates were further characterized by determining the roundness and sphericity values of particle shapes. Highlights of the asphalt cement findings, as well as those of the aggregates, are noted.

### 4.1 Coarse Aggregates: Percent Crushed and P.N.

The percentage of crushed particles for the different sources of coarse aggregates ranged from 53% to 100%, while the P.N. varied from 100 to 139 as displayed in Table 1. At 53% the carbonate-gneiss gravel of mix #4 had the lowest percent crushed aggregate content although its P.N. was excellent at 104. The highest or poorest P.N., 139, belonged to the 67% crushed coarse aggregate from mix #6.

### 4.2 Aggregate Particle Shape Data

On a scale rating from 0.1 to 1.0, the coarse aggregates (C.A.) were classified as to their roundness and sphericity (Table 2) by comparison with the Roundness Sphericity Chart in Figure 2 (5). It was hoped that these two classifications might give an indication of aggregate rutting tendency. Sphericity rates the particle's increasing resemblance to a spherical shape for a maximum rating of 1.0 whereas roundness rates the particle's lessening degree of angularity to obtain a maximum rating of 1.0. The methodology used in the evaluation of these parameters by the laboratory is outlined in Appendix A.

As low roundness values indicate high particle angularity, this property is expected to generate good particle interlock and high interparticle friction in the aggregate matrix. Low sphericity values indicate elongated particles that align more horizontally under the kneading action of paving rollers and traffic tires, producing greater probability of coarse aggregate particle interaction and hence greater rutting resistance.

Three of the four naturally occurring aggregates with 100% crushed coarse particles had low roundness and sphericity ratings of 0.2 or less. The sphericity rating increased to 0.4 for the fourth coarse aggregate from mix #11 (Harnden and King).

The roundness and sphericity combinations of mix #2 at 0.6 and 0.7 respectively and mix #4 at 0.7 and 0.6 respectively were the highest of the coarse aggregates, although mixes #6 and #10 were very close at 0.6. These last four mixes, #2, 4, 6, and 10, were considered to have rutting potential.

While the slag aggregates had a roundness value of only 0.2, their sphericity values were higher than average at 0.6.

The same roundness and sphericity classifications were applied to the fine aggregates (F.A.) in the mixes. These particles were sized and the ratings given as a weighted percent for each size. For the fine aggregates other than screenings, all mixes exhibited similar values, 0.3 to 0.4 for roundness and 0.4 to 0.5 for sphericity. These sands would therefore be expected to have similar effects on rutting as far as roundness and sphericity were concerned.

The screenings from mixes #4 and #8 had low roundness values of 0.1 and sphericity values of 0.1 to 0.2. In contrast, the slag screenings from Steetley had a roundness rating of 0.3 and a high sphericity of 0.6.

## 4.3 Asphalt Cement Data

Nine of the eleven mixes used an 85/100 penetration grade asphalt cement. A 150/200 grade was used for Contract 86-202 from Northern Region and a 300/400 grade was used for Contract 86-38, a recycled hot mix from Southwestern Region. Imperial Oil, Montreal, and Petro Canada, Bronte, supplied the respective asphalt cements, all of which met M.T.O. specifications (6). Table 3 has test results for the three original asphalt cements and the R.A.P. A.C.

In the course of relating asphalt test results to mix properties, the penetration indices (P.I.) of the asphalt cements were obtained. Test data from penetrations and absolute viscosities were used. As with many asphalts, the softening points digressed from the best fit line and were therefore not used for the determinations. The P.I. ranged from -1.2, i.e., for the 300/400 penetration grade A.C. to -0.7, i.e., for the 85/100 penetration grade A.C. In between was the 150/200 asphalt cement with a P.I. of -1.0. It should be noted that the slope of the log-log viscosity versus log temperature plot for all three virgin A.C. in the 'Bitumen Test Data Chart' (Fig. 3) are very close, a possible indicator of similar temperature susceptibilities. The R.A.P. recovered A.C. produced a low P.I. of -2.7.

Also, the asphalt cements of the prepared mixes were recovered and tested. The P.I. were found to have increased to +0.5 for the 85/100, -0.1 for the R.H.M. and -0.6 for the 150/200.

## 4.4. Mix Design Data

All of the mixes were designed according to the Ministry's Laboratory Standards Manual (7) and Provincial Standard Specifications (6). The gradations and design data can be found in Tables 4 and 5 respectively and, based mainly on the maximum particle size, the mixes can be divided into 4 groups.

| Group | Mix Number | Mix Type | Maximum Particle Size (mm) |
|---|---|---|---|
| 1 | 1, 2, 10 | H.L.-1, H.L.-3, H.L.-3 R.H.M. | 16 |
| 2 | 3, 4, 11 | H.L.-4's | 19 |
| 3 | 7, 8<br>9 | D.F.C., Mod. D.F.C.<br>O.F.C. | 16<br>13.2 |
| 4 | 5, 6 | H.L.-8's | 26.5 |

The excerpt below of Group 1 from Table 5 shows that mix #1, an H.L-1, has a %V.M.A. of 14.9, slightly below the required 15.0% minimum. Also, the use of two grades of A.C., 85/100 and 300/400, may have contributed to the wide spread of the stabilities from 10200 Newtons (N) to 16700 N (2300 to 3760 lbf) in the group.

| Mix # | H.L. Type | A.C. Grade | % A.C. | Stability (N) | % Voids | % V.M.A. |
|---|---|---|---|---|---|---|
| 1 | 1 | 85/100 | 5.1 | 16700 | 4.1 | 14.9 |
| 2 | 3 | 85/100 | 5.4 | 11500 | 3.0 | 15.7 |
| 10 | 3 R.H.M. | 300/400 | 5.2 | 10200 | 3.7 | 15.4 |

For Group II below, the surface dry voids for mix #11 were slightly low at 2.5% whereas specifications call for a minimum of 3%. Likewise low was the %V.M.A. of mix #3 at 13.8% where 14.5% was required. Note that mix #11 was a slightly finer mix, retaining only 40% of material by mass on the 4.75 mm (#4) sieve compared to 45% for the other two mixes in the group.

| Mix # | H.L. Type | A.C. Grade | % A.C. | Stability (N) | % Voids | % V.M.A. |
|---|---|---|---|---|---|---|
| 3 | 4 | 85/100 | 5.3 | 13600 | 4.0 | 13.8 |
| 4 | 4 | 85/100 | 4.8 | 10200 | 3.0 | 15.1 |
| 11 | 4 | 150/200 | 5.2 | 10100 | 2.5 | 15.2 |

Mixes #7 and #8 (Group III below) differed in that steel slag was used for #7 while #8 was made of sandstone aggregates. Because of a 10% increase in material retained on the 4.75 mm (#4) sieve for mix #8 and

the highly absorptive aggregate used for mix #7, the mix design A.C.% was quite different for the two mixes. A 5.6% A.C. content was used for mix #7 whereas only 4.7% A.C. was used for mix #8. The higher A.C. content resulted in a surface dry voids of 1.6% for the steel slag mix. Due to a low aggregate water absorption of 0.5%, the surface dry void content for mix #8 was not done; however, a conservative correction of 0.3% would lower its voids from 2.6% down to 2.3% (surface dry).

| Mix # | H.L. Type | A.C. Grade | % A.C. | Stability (N) | % Voids | % V.M.A. |
|---|---|---|---|---|---|---|
| 7 | D.F.C. | 85/100 | 5.6 | 16200 | 1.6 | 13.5 |
| 8 | Mod. D.F.C. | 85/100 | 4.7 | 14800 | 2.3 | 13.8 |
| 9 | O.F.C. | 85/100 | 5.2 | 11800 | 5.3 | 16.2 |

Group III also contains an O.F.C., another type of mix containing 100% washed aggregates from the same source as mix #7 (Table 5) but which uses 13.2 mm ($\frac{1}{2}$ in) as its maximum aggregate size. Note that it retained at least 10% more material on the 4.75 mm (#4) sieve than the other two mixes in the group. Unfortunately, as no other O.F.C. contracts were available, only one mix of this type was used for the experiment.

As shown below, the stabilities of the HL8 mixes from Group IV were within specification limits but at the low end, i.e., 10300 N (2320 lbf) and 9100 N (2040 lbf). This occurred even though the mixes possessed good %V.M.A. values of 15.7 and 16.2 respectively and used aggregate with the largest nominal particle size of any of the project mixes.

| Mix # | H.L. Type | A.C. Grade | % A.C. | Stability (N) | % Voids | % V.M.A. |
|---|---|---|---|---|---|---|
| 5 | 8 | 85/100 | 5.3 | 10300 | 4.0 | 15.7 |
| 6 | 8 | 85/100 | 5.5 | 9100 | 3.0 | 16.2 |

## 4.5 Field Sample Data

Samples from the Bloomington Road pavement consisted of an H.L.-3 surface mix over an H.L.-8 binder with both mixes containing 1.5% asbestos. The other pavement samples from Highway 401 consisted of an

H.L.-1 mix placed above an H.L.-4 binder course. Pavement investigation data from all of these sites can be found in Table 6 (8). In spite of any asphalt hardening caused by reheating of the mix during recompaction, low stabilities of 5600 N (1260 lbf) and 8200 N (1840 lbf) and low voids of 1.5% and 1.7% were obtained for the H.L.-3 and H.L.-8 mixes respectively from Bloomington Road.

## 5. EXPERIMENTATION

A Wheel Tracking Machine is used for the rutting of the test specimens. To produce samples that have similar particle orientations and densities as those occurring in the field, a kneading compactor was used by a trial and error method to obtain appropriate beam densities. While a brief description of the equipment, sample preparation, and testing follows, the complete procedure used is described under the decreasing temperature mode of testing in Appendix B of the report "Using A Wheel Tracking Machine For Evaluation Of Asphalt Rutting" (9).

### 5.1 Wheel Tracking Machine

The machine allows repeated passes of a weighted tire over a specimen along a wheel path at the rate of 64 passes per minute. Immersion of specimens in a temperature controlled bath with overhead surface heating by infrared lamps permits effective control of specimen temperatures.

#### 5.1.1 *Tire Type*

With a sample surface area of 381 x 140 mm (15 x 5.5 in) and restricted tire travel length, a small pneumatic treaded tire produced by the Goodyear Tire and Rubber Company with a tread width of 70 mm (2.76 in) was selected for use with the W.T.M. rather than the treadless tire used by others (10). It is designated by Goodyear as a 4.10-4 industrial tire with a 4 ply rating and a Shore Durometer Hardness 70. This value is similar to the hardness of tires commonly used by highway vehicles.

### 5.1.2 *Tire Loading and Pressure*

The wheel carries a load of 65.5 kg (144.4 lb) which is the maximum that can be held by the W.T.M wheel carriage assembly (Fig. 4). That is approximately 10% of the maximum load (Appendix B) allowed by the Compliance Branch of the Ministry (11).

An inflation pressure of 550 kPa (80 psi) was used to approximate the average bias ply pressure of truck tires on highways as determined by the Ministry survey (2).

## 5.2 Sample Preparation and Conditioning

Although the complete method for manufacture and conditioning of the beams is given in a previous study (9), a brief description follows.

### 5.2.1 *Laboratory Samples*

All laboratory produced beams consisted of two lifts, each 38 mm (1.50 in) thick, of mixes from selected mix designs. The bottom lift of each beam was manufactured using a high stability (13600 N or 3060 lbf) Durham H.L.-4 mix compacted to a bulk relative density (B.R.D.) equivalent to 96 ± 1% of Marshall density. Each specified top lift was manufactured with the same compactive effort as for the Durham mix above a bottom lift which had been allowed to cool overnight to room temperature.

A modified A.S.T.M. method (12) was used to make the beams by means of a California kneading compactor with the finishing levelling load being applied by a compression machine. Thermocouples were placed approximately 6 mm ($\frac{1}{4}$ in) above both the mould bottom and the interface between the two lifts during sample manufacture. Temperature readings from these were displayed by an Omega 981 Digital Thermometer while beam surface temperatures were measured using the Raytek Raynger II non-contact infrared sensing thermometer gun.

Transverse surface profiles of the new beam were taken at the middle and end-points of wheel travel using profilometers. The beam assembly was covered and placed back in the oven until temperatures were slightly above the initial testing requirement. After removal at this time from the oven, the mould sides were immediately insulated with styrofoam and the specimen was completely surrounded by a thermal blanket. When the surface and interface temperatures decreased to ± 1°C (± 2°F) of the intended initial testing temperatures, the blanket was removed, and the beam and mould assembly was immersed in the W.T.M. 60°C water bath to a depth of 13 mm ($\frac{1}{2}$ in). With the exposure of the beam's top and bottom surfaces to the infrared lamps and to the 60°C constant temperature of the bath, the specimen was ready for testing.

5.2.2 *Field Samples*

For the field samples, beams were formed by sawing the pavement sections to fit the inside mould dimensions of 381 mm length x 140 mm width x 76 mm depth (15 x 5.5 x 3 in). After overnight conditioning of the beam and mould assemblies in an air bath at 60°C, the field specimens were insulated and placed in the W.T.M. for testing at 60°C.

5.3 Test Procedure

Testing was completed in slightly over two hours. During the testing, temperatures were monitored via inserted thermocouples. These readings included W.T.M. bath temperatures and the base and interface temperatures of the specimen. For recording the beam surface temperatures and the transverse profiles (Fig. 5) at the preselected positions determined in Section 5.2.1, the W.T.M. was stopped for approximately 30 seconds during the testing at 500, 1 000, 2 000, and 4 000 passes.

After 8 000 passes, the tested beams were allowed to cool overnight before extrusion, examination, and sawing. Bulk relative density measurements were then determined for the mix portions under and adjacent to the wheel tracks.

## 6. RESULTS AND DISCUSSION

Rutting occurred to some extent in all samples. Differences in rutting between 60°C and 100°C initial test temperatures are illustrated by the photographs of beam cross-sections in Figures 6 to 9. The beams in the pictures represent the four groups of mixes described in Section 4.4. The least rutted mix was the D.F.C. (Fig. 8) of Group III, shown with the modified D.F.C. and the O.F.C. One of the two H.L.-8 mixes of group IV using 26.5 mm (1 in) maximum size aggregate had the most rutting (Fig. 9).

For some mixes, signs of deformation appeared within the first fifty passes. Shortly after, side mounding or pushing of the mix adjacent to the track became visible, accompanied by hairline cracking along the same areas. On some of the deeply rutted beams, the tracked area appeared flushed as a result of asphalt cement being squeezed to the surface by the tire action.

Most beam cross-sections showed very little distortion at the lift interfaces indicating that negligible rutting of the bottom lift had taken place, even at the 100°C initial temperature. However, slight bottom lift deformation was visible where top lift rutting was severe, as in the case of mixes #6, 10, and 11. This occurs because the tire sits lower in the mix which increases the stress on the lower lift. The force exerted by the tire tends to displace the mix from under the tire resulting in the pushing up of the beam sides and to horizontally orient the coarse aggregate particles as seen in some of the cross-section photographs. These disturbances cause mix density changes (Table 7) both under and beside the wheel track.

The ruts in the pictures appear to be greater than the amounts given in Table 8 because the tabulated data show only the rut depths measured from the original surface levels to the final depths.

A typical rutting-time curve (Fig. 10) shows that there was an initial rapid rate of deformation followed by a slow incremental rate to the end of testing. As the rate of rutting for the final 4 000 passes was slow,

testing was discontinued at the 8000 pass mark. In general, some inconsistencies exist in the rutting-time curves because of the different degrees of aggregate interlock at the three transverse profile positions.

## 6.1 Effect of Initial Test Temperature

When tested at increasing initial temperatures, the beams produced a family of curves showing successively greater rut depths for a given number of passes (Figs. 11a to 11c). The average rut depth of all mixes after 8000 passes at a base temperature of 60°C was 3.8 mm (0.196 in) whereas the average rut depth using 100°C as the initial temperature was 10.0 mm (0.394 in), i.e., a ratio of 1:2.65. Compared with an average rut depth of 5.0 mm (0.196 in) at an initial test temperature of 70°C, a ratio of 1:1.33 was produced. By lowering the initial test temperature from 100°C to 70°C, the amount of rutting due to wheel load was reduced by half.

When tracking of the sample was reduced from 8000 to 4000 passes, a similar improvement in the magnitude of the rutting occurred upon lowering the initial test temperatures. The average rut depth of all mixes at 60°C was 3.0 mm (0.118 in), at 70°C was 4.4 mm (0.174 in), and at 100°C was 9.2 mm (0.362 in). The ratios of the rut depths at 60°C relative to 100°C and 70°C were 1:3.07 and 1:1.47 respectively.

In order to assess the effect of even lower temperatures on rutting, beams of mix #3 utilizing the Durham coarse and fine aggregates were tested at a constant temperature of 30°C. Only 0.5 mm (0.020 in) of rutting was produced after 8000 passes. This indicates that cooling of the mats to ambient air temperatures can further reduce the potential for rutting by traffic after construction.

The practical implication of the above findings is that, by allowing a newly compacted mat to cool somewhat before opening to traffic, substantial benefits by a reduction in rutting can be realized by just a slight delay of traffic for one hour. With a small breeze and/or air temperatures lower than 30°C, the cooling period could even be shorter.

## 6.2 Effect of Increasing Wheel Passes

At 500 passes and at 60°C, mix #7 and mix #11 represent the best and the poorest mixes respectively. By increasing the initial test temperature from 60°C to 100°C the level of rutting of these mixes was much higher, producing an increase of 1000% (from 0.2 to 2.2 mm or 0.008 to 0.086 in) and 107% (from 2.8 to 5.8 mm or 0.110 to 0.228 in) respectively. While mix #7 still rutted the least at 100°C, mix #10 at 6.8 mm (0.268 in) surpassed mix #11 as the most rutted mix.

At 2000 passes and at 60°C, mix #7 showed minimal rutting of 0.7 mm (0.028 in) while mix #11 displayed the greatest rut depth at 4.5 mm (0.178 in). As the initial temperature rose, rutting of all mixes increased. At 100°C, mix #6 produced the deepest rutting at 15.3 mm (0.602 in). This represents a 488% increase relative to that produced at 60°C by the same mix. Even mix #7, one of the most rut resistant mixes found on highways, produced a 414% increase in rutting at an initial temperature of 100°C over that at 60°C.

The same pattern held true at 4000 passes but at higher levels of rutting. At the higher temperatures, the percentage increases were less than those found at 2000 passes. Rutting for mix #6 rose 267% while that for mix #7 increased by 310% over that at 60°C.

The continued increases in rut depth with numbers of passes verifies the fact that pavement damage is a function of the numbers of heavy axle loadings over a stretch of highway.

## 6.3 Rut Depth Development

The rutting pattern shown in Figure 10 can be divided into two distinct stages, viz., initial mix compaction with accompanying volume change and final deformation without volume change.

The stage with volume change can itself be divided into two periods. At the outset of testing, a compaction deformation period is characterized by

a lack of mounding adjacent to the wheel track and accompanied by a rapid rate of rutting. As indicated by the transverse profiles (Fig. 12), mounding at an initial temperature of 60°C appears to be delayed until approximately 2000 passes. A transition period follows from 2000 to 4000 passes during which mounding makes its appearance accompanied by a decreasing rate of deformation.

As initial test temperatures are increased, mounding is found to occur earlier for each mix. Also, the total number of passes in the compaction stage decrease because the mixes achieve maximum density earlier. In this study, about 40% to 95% of the total rutting occurred within the compaction stage.

The first 500 passes of the compaction stage produced the greatest change in rut depth. Figures 13a to 13c clearly demonstrate the rutting effect of the first 500 passes relative to the final 4000 passes of the experimentation. The change in rut depth between 0 and 500 passes shall hereafter be referred to as 'initial rut' and the rut depth between 4000 and 8000 passes, as 'final rut'.

For tests with an initial beam temperature of 100°C, the ratio of the average 'initial rut' rate to average 'final rut' rate is 57:1. Even at a lower test temperature, i.e., 60°C, the difference is very noticeable with $2.55 \times 10^{-3}$ mm/pass for the 'initial rut' rate and $2.00 \times 10^{-4}$ mm/pass for the 'final rut' rate giving a ratio of 13:1. Hence, irrespective of initial temperature, the rutting rate appears to be much higher for the 'initial rut' period than for the 'final rut' period, the extent differing with each type of mix.

## 6.4 Indicator for Mix Evaluation

The final 4000 to 8000 passes of the testing represents the second stage of rutting, a steady state period during which mounding continues to occur. Although the rate is small, deformation is constant and differs only slightly between mix groups. An examination of temperature gradients (Fig. 14) reveals that initial beam temperatures of 100°C had

decreased to an average of 70°C by 2000 passes and to 63°C by 4000 passes. At this point the system is essentially at constant temperature which explains why the rates of rutting of all mixes after 4000 passes differed only slightly.

The slight differences in rutting rates between the mix groups during this period are related to the characteristics of each mix. This steady state period is considered a good indicator of the rutting potential of the different mixes at the maximum densities encountered in the field along the wheel tracks.

Because the initial percent compaction within each mix group is similar and since the rutting rate for each mix in the group is constant for the last 4000 passes, the difference in total rutting rate of mixes within the group must again be due to the 'initial rut' rate caused by the different initial test temperatures.

## 6.5 Rutting by Mix Type

If the rut depth of each mix at 8000 passes is plotted against different temperatures, the rut depth differences between the eleven mixes widens with an increase in temperature (Fig. 15). Mixes #1 (H.L.-1) and #7 (D.F.C.) with a high resistance to rutting had the lowest sloping lines. These are followed by H.L.-3 or H.L.-4 which exhibited steeper slopes (except for mix #11) and therefore greater rut depths with increasing temperature. The H.L.-8 mixes used as binder layers also displayed steep slopes and, on average, rutted the most with increasing temperature.

## 6.6 Mix Parameters

As noted in Figures 16a to 16e, the eleven mixes did not all rut the same amount per pass. Some of the mixes such as #6 and #10 rutted relatively faster than the others with rising temperatures. Also, an increase in temperature accentuated the variations in rutting between some of the mixes. Many of these variations were found to be due to the differences in

mix parameters as a result of the types of asphalt cement and aggregate used.

6.6.1 *Asphalt Cement Penetration Grade*

As noted in Section 6.5, the slope of the line (Fig. 15) for mix #11 is unusual when compared with its high rutting value obtained at 60°C. A cause may be the use of a 150/200 binder. The 'Shell Bitumen Test Data Chart' (Fig. 3) indicates that the viscosities of the 85/100 and 150/200 grade A.C. would be similar if the 150/200 was 11°C cooler. Superimposing the line for mix #11 (Fig. 15) to the right of its present position by 11°C and extrapolating this new line position back to 60°C gives slope patterns comparable with the other mixes. This indicates that mix #11 might be a reasonably rut resistant mix if its binder were an 85/100 grade A.C., i.e., one penetration grade lower.

6.6.2 *Effect of Asphalt Cement Stiffness*

Since the penetration index of the R.H.M. A.C. was between that of the 85/100 and 150/200 A.C. grades and the W.T.M. loading frequency for all these mixes was identical, the asphalt cement 'stiffness' of the R.H.M. must also be intermediate. The asphalt 'stiffness' values were estimated on the basis of Van der Poel's nomograph (1) and the associated equations. When derived at 1.07 Hz, which represents the loading frequency of the W.T.M., the estimated 'stiffness' of the R.H.M. asphalt cement for temperatures from 60 to 100°C varied from $7.14 \times 10^{-2}$ to $0.102 \times 10^{-2}$ kg/cm$^2$ respectively.

However, the above results represent only 0.06 to 0.03% of the mix 'stiffnesses' at the temperatures concerned, from $1.24 \times 10^2$ to $0.039 \times 10^2$ kg/cm$^2$ respectively. The R.H.M. mix 'stiffness' was approximately 50% (Fig. 17) of that produced by the mixes containing 85/100 grade asphalt. For mix #11, the mix 'stiffness' was approximately 35% of that exhibited by the 85/100 grade mixes for the range of temperatures used.

Increasing mix temperature reduces the stiffness effect of the A.C., allowing aggregate properties to play a more dominant role in as far as rutting potential is concerned and thereby making the asphaltic concrete act more like a granular mix. This explains the fact that mixes #10 and 11 have rutting similar (Figs. 16a to 16e) to mixes #2, 3, 4, and 5 after 500 passes from 100°C because beam temperatures are still high.

A comparison of 'final rut' to 'initial rut' at 100°C indicates that mixes #10 and #11 exceeded the rutting of all mixes including mix #6. As the temperature drops, the higher stiffness of the 85/100 A.C. is now more dominant in resisting rutting as shown by the ratio of 'final rut' to 'initial rut' (Fig. 18). Mixes #1 to #9 had a 9.45:1 average whereas mixes #10 and #11 had a 3.6:1 average.

At a test temperature of 60°C the lower mix 'stiffnesses' of #10 and #11 cause these mixes to have comparable or slightly higher rutting rates than the other mixes throughout the experimentation.

6.6.3 *Aggregate Properties*

Rutting produced by those mixes containing 100% crushed C.A. (mixes #1, 5, 7, 8, 9, 11) averaged 8.2 mm (0.322 in) after 8000 passes at an initial temperature of 100°C. If mix #11 is excluded for the reasons discussed in the previous section, the average decreased further to 6.9 mm (0.272 in). The remainder of the mixes not using 100% crushed C.A. averaged 12.1 mm (0.476 in) of rutting, an increase of 75%. Therefore, mixes with the higher percentage of crushed C.A. appear to show more resistance to rutting at higher temperatures.

The graphs also indicate that rutting is affected by aggregate shape parameters such as roundness and sphericity. Correlation coefficients of R=0.46 to R=0.80 are produced when comparing the dependence of rutting on roundness (Figs. 19a to 19d), excluding mix #11 with its softer A.C.

An attempt was made to separate the interaction of C.A. roundness and sphericity values on rutting. Mixes #1, 5, 7, 8, 9, and 11 with the same

C.A. roundness value of 0.2 showed no trend between rutting and sphericity even when mix #11 using the softer A.C. was excluded.

However, the effect of C.A. roundness on rutting was greater. Mixes #4, 6, 7, 9, and 10 with the same C.A. sphericity value of 0.6 showed decreasing rutting with roundness (Figs. 20a to 20d), with or without mix #10 containing some softer A.C. Because the number of data points were few and were clustered in two groups, the trends showing average correlation coefficients of R=0.81 should be viewed with caution.

The narrow range of F.A. sphericity and roundness, only 0.1 units for either parameter, made examination of their effects on rutting difficult. In any case, no trend was observed. However, it was noted that for three of the four mixes containing screenings, rutting was generally low. The rut depth of mix #4 was high, in contrast with the low rut depths of mixes #7, #8 and #9, because of the low 53% crushed C.A. used.

In summary, an increase in the percentage of crushed content in the coarse aggregate appears to decrease rutting. The F.A. data also suggests that screenings may be a deterrent to rutting. Greater rutting also results from the use of C.A. with increasing particle roundness but is less affected by particle sphericity. Since the roundness value is an average measure of both crushed and uncrushed particle values, then both roundness values and the percentage of crushed particles reflect the same physical material property that is important in reducing rutting - mainly aggregate angularity resulting in greater support for higher stresses.

### 6.6.4 *Mix Design Properties*

An inverse relationship between Marshall design stability values and rutting is evident regardless of initial beam test temperature or duration of testing (Fig. 21a to 21d). The graphs, showing rutting decreasing with increasing stability values, have correlation coefficients ranging from R=0.78 to R=0.91 for the various initial test temperatures.

A comparison of 'initial rut' and 'final rut' periods with Marshall stability values shows that the high correlation coefficient of R=0.88 exists only during the 'initial rut' period when compaction takes place. For the final rutting period, the correlation coefficient drops dramatically to approximately R=0.46. Hence, Marshall values are good indicators of the potential of mixes to rut initially during the compaction stage when the percentage of voids are being reduced. But due to the impact of the high 'initial rut' period on total rut depth, the Marshall stability data correlated well overall with total rut depths even when the 'final rut' period was included.

A reasonable trend of decreasing rutting is also visible when compared with increasing percent voids (Figs. 22a to 22d). This may suggest that mix design voids should be set toward the maximum end of specification limits, i.e., 5%, to minimize rutting; however, further study should be undertaken to corroborate that indicator.

In summary, many mix parameters appear to affect rutting. The evaluation reveals that the least rutting exhibited by mixes #1 and 7 at both 60 and 100°C can be attributed to the use of 100% crushed aggregate with a very low aggregate roundness and the use of the 85/100 penetration grade asphalt cement. The low rutting potential of these mixes is reflected by the very high stability values.

At the other end of the scale, the most rutting was produced by mixes #6, 10, and 11 when tested at 100°C. Mix #6 containing an 85/100 penetration asphalt cement ruts more than the other mixes because of its high roundness value and only 67% crushed coarse aggregate content. Its lower stability differentiates it from mix #4 which possesses slightly less crushed coarse aggregate.

The rut depths of mixes #10 and #11 are similar to those of mixes #2, 3, 4, and 5 after 500 passes from the 100°C test temperature, due to similar aggregate quality and because the asphalt stiffnesses are less influential as temperatures are still high. By 8000 passes, as the temperatures decrease and the rutting of mixes #2, 3, 4, and 5 is restrained more by the

effect of the lower penetration asphalt, the rutting of mixes #10 and #11 progresses at a relatively higher rate. At a constant temperature of 60°C, mixes #10 and #11 also rut relatively faster than the other mixes because of the softer asphalt cement used.

The greater rutting of mix #10 over mix #11 is related to differences in percent crushed coarse aggregate and roundness values offset to a degree by the stiffer asphalt of mix #10. Low Marshall stabilities reflect the high rutting potential of these mixes.

## 6.7 Evaluation of Field Samples

Although the field samples were tested at 60°C only, they exhibited a wide range of rutting behaviour relative to the laboratory manufactured beams. Graphs of rut depth to number of passes produced by the three field mixes tested to 8000 passes appeared similar to those produced by the laboratory manufactured samples.

Two of the samples marked trench 'A' and trench 'B', produced 3.6 and 5.2 mm (0.142 and 0.204 in) of rutting respectively after 8000 passes even though much of the compaction had already been achieved by traffic. These amounts were comparable to those produced by laboratory mixes #8 and #6. At the other extreme, the Port Hope Highway 401 specimen at 10.9 mm (0.430 in) after 8000 passes and the Bloomington Road sample at 34.7 mm (1.366 in) after only 500 passes displayed rutting far above that of the laboratory manufactured specimens.

Also, the rutting versus stability curve produced by the laboratory specimens at 60°C is similar to that for the field samples (Fig. 23). These results indicate that the four field specimens produced greater amounts of rutting than do the laboratory mixes at similar stability levels. A partial cause may be the lack of wall friction between the field samples and mould walls.

## 6.8 Relationship of W.T.M. Passes to Traffic

On some sections of Hwy. 401, the traffic volume is recorded at 320000 A.A.D.T. (4) with 10% being truck traffic. Assuming that two thirds of the traffic pass through during the twelve hour daylight period, the number of wheel passes for one of the 12 lanes could be over 3000 per hour. Therefore, the cooling rate (Fig. 14) used for the experimentation and the number of wheel passes per hour (3840 passes) correspond favourably to the conditions on some of the high traffic volume roads. These facts further confirm the role that the W.T.M. could play in screening mixes in the laboratory to avoid rutting damage by traffic during the first hour of cooling.

## 7. CONCLUSIONS

This study has dealt with the effect of temperatures on the permanent deformation of mixes under simulated traffic action by using the Wheel Tracking Machine. The main finding is that the amount of initial rutting is directly proportional to the testing temperatures, i.e., the hot mix temperatures at which traffic is allowed to travel on newly constructed pavements. Compared to rutting at 60°C, the rutting increased by an average of 33% at 70°C, 83% at 85°C and 165% at 100°C.

Other findings are:

a) mix types used on high traffic volume roads had the least rutting in the study. This confirms that the current policy governing the use of D.F.C., O.F.C. and HL-1 mixes is correct.

b) field specimens of pavements with a problem of rutting produced the most deformation.

c) decompaction of the mixtures adjacent to the wheel tracking area was found to be caused by the reorientation of the aggregate particles.

d) mixes using coarse aggregates with low roundness values - or high angularity, synonymous with higher percent crushed content - rutted less.

e) mix designs which had high Marshall stability values had low rut depth measurements.

f) although the data is limited, it appeared that under similar temperature conditions, the lower stiffnesses of the higher penetration asphalt cements increased the rutting potential of the mixes using those asphalts.

## 8. RECOMMENDATIONS

In view of the findings, it is recommended that:

a) specifications should include a maximum mat temperature of 60°C before traffic be allowed on freshly laid pavements.

b) the scope of the study should be extended to include relatively new mixes such as the heavy duty binder courses and large stone mixes.

c) a study should be initiated to confirm the relationship between coarse aggregate roundness and percent crushed content and the use of high roundness value aggregates in reducing rutting.

d) a study should be initiated to confirm the apparent increased rutting effects produced by the use of softer asphalt cement grades, and in particular, their temperature related rutting effects.

e) for the mixes which were tested by the W.T.M. for this study, field performance should be closely monitored to correlate truck and traffic volumes with W.T.M. results for future rutting studies.

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## Table 1 AGGREGATE SOURCES AND PROPERTIES

| Mix # | H.L. Type | Coarse Aggregate | % Crushed | P.N. | Fine Aggregate #1 | Fine Aggregate #2 | Screenings |
|---|---|---|---|---|---|---|---|
| 1 | 1 | quarried traprock (metavolcanic) 3M Havelock MAI# C1-54 | 100 | 100 | carbonate Durham MAI#D6-5 | | |
| 2 | 3 | 85% carbonate 15% granite Oak Park MAI#B13-76 | 77 | 125 | Oak Park MAI#B13-76 | | Oak Park MAI#B13-76 |
| 3 | 4 | 95% carbonate 5% granite Durham MAI#D6-5 | 80+ | 115 | carbonate Durham MAI#D6-5 | | |
| 4 | 4 | 90% sandy carbonate 10% granite gneiss TRT MAI#S2-39 | 53 | 104 | TRT MAI#S2-39 | | TRT MAI#S2-39 |
| 5 | 8 | dolostone Taro MAI#G8-2 | 100 | 122 | Oak Park MAI#B13-76 | | |
| 6 | 8 | 90% carbonates,sandstones 10% granite gneiss Vicdom MAI#N2-124 | 67 | 139 | carbonate,granitic material Miller MAI#N2-77 | | |
| 7 | D.F.C. | slag(unwashed) Steetley MAI#H3-12 | 100 | --- | | | slag(unwashed) Steetley MAI#H3-12 |
| 8 | Modified D.F.C. | quartz sandstone,carbonates Armbro MAI#O5-72 | 100 | 126 | | | Armbro MAI#O5-72 |
| 9 | O.F.C. | slag(washed) Steetley MAI#H3-12 | 100 | --- | | | slag(washed) Steetley MAI#H3-12 |
| 10 | H.L.-3 R.H.M. | 85%carbonates,sandy carbonates 15% granite gneiss TCG MAI#B13-17 | 80 | 125 | 85%carbonate,sandy carbonates 15% granite gneiss Shelton MAI#W11-15 | | |
| 11 | 4 | dolostone,argillaceous carbonates Hamden & King MAI#K10-21 | 100 | 102 | McLennan MAI#M11-24 | carbonate, minor granitic Ferguson MAI#K10-32 | |

**Table 2 AGGREGATE ROUNDNESS AND SPHERICITY VALUES**

| Mix # | Coarse Aggregate | | Fine Aggregate | | Screenings | |
|---|---|---|---|---|---|---|
| | Roundness | Sphericity | Roundness | Sphericity | Roundness | Sphericity |
| 1 | 0.2 | 0.1 | 0.4 | 0.5 | n.r. | n.r. |
| 2 | 0.6 | 0.7 | 0.3 | 0.5 | Oak Park - n.a. | |
| 3 | 0.5 | 0.5 | 0.4 | 0.5 | n.r. | n.r. |
| 4 | 0.7 | 0.6 | 0.3 | 0.4 | 0.1 | 0.1 |
| 5 | 0.2 | 0.2 | 0.4 | 0.5 | n.r. | n.r. |
| 6 | 0.6 | 0.6 | 0.4 | 0.5 | n.r. | n.r. |
| 7 | 0.2 | 0.6 | n.r. | n.r. | 0.3 | 0.6 |
| 8 | 0.2 | 0.2 | n.r. | n.r. | 0.1 | 0.2 |
| 9 | 0.2 | 0.6 | n.r. | n.r. | 0.3 | 0.6 |
| 10 | 0.6 | 0.6 | 0.4 | 0.4 | n.r. | n.r. |
| 11 | 0.2 | 0.4 | McLennan - n.a. 0.4 | 0.5 | n.r. | n.r. |

n.a. = not available
n.r. = not required

## Table 3 ASPHALT CEMENT TEST RESULTS

| PROPERTIES | Imperial Oil 85/100 | PetroCanada 150/200 | PetroCanada 300/400 | R.A.P. |
|---|---|---|---|---|
| Pen. @ 4°C, 100 g, 5 s | 9 | 15 | 30 | |
| Pen. @ 4°C, 200 g, 60 s | 31 | 50 | 112 | |
| Pen. @ 10°C, 100 g, 5 s | 18 | 32 | 59 | |
| Pen. @ 25°C, 100 g, 5 s | 90 | 179 | 380 | |
| Softening Point (R&B), °C | 46.8 | 40.6 | 34.7 | |
| Abs. Visc. @60°C, Pa.s | 152 | 51.8 | 18.6 | |
| Kin. Visc. @ 121.1°C, mm^2/s | 727 | 424 | 242 | |
| Kin. Visc. @ 135°C, mm^2/s | 338 | 220 | 131 | |
| Kin. Visc. @ 148.9°C, mm^2/s | 189 | 125 | 79 | |
| Relative Density @ 15.6°C | 1.026 | 1.022 | 1.009 | |
| C.O.C. Flash, °C | 308 | 306 | 292 | |
| % Solubility in Tri. | 99.96 | 99.99 | 99.99 | |
| Duct. @ 4°C, cm | 15+ | 15+ | 150+ | |
| % Loss by Thin Film Oven | 0.11 | -0.034 | -0.012 | |
| THIN FILM RESIDUE TESTS | | | | |
| Pen. @ 25°C, 100 g, 5 s | 55 | 107 | 235 | |
| % Original Penetration | 61 | 60 | 62 | |
| Duct. @ 25°C, cm | 100+ | 100+ | 100+ | |
| AFTER ABSON RECOVERY TEST | | | | |
| Pen. @ 25°C, 100 g, 5 s | | | | 38 |
| Abs. Visc. @ 60°C, Pa.s | | | | 711 |

## Table 4 MIX GRADATIONS

| Mix# | H.L. Type | Sieve Size 19.0 mm | 16.0 mm | 13.2 mm | 9.5 mm | 6.7 mm | 4.75 mm | 2.36 mm | 1.18 mm | 600 um | 300 um | 150 um | 75 um |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H.L.-1 | ----- | ----- | 0.1 | 19 | 37 | 45 | 52 | 60 | 72 | 90 | 96 | 98.1 |
| 2 | H.L.-3 | ----- | ----- | ----- | 16 | ----- | 45 | 53 | 63 | 76 | 91 | 96 | 97.6 |
| 3 | H.L.-4 | ----- | 2 | 11 | 31 | 41 | 45 | 55 | 64 | 74 | 87 | 94 | 96.5 |
| 4 | H.L.-4 | ----- | 1 | 4 | 20 | ----- | 45 | 54 | 61 | 70 | 87 | 95 | 97.2 |
| 5 | H.L.-8 | 1 | 5 | 10 | 32 | 43 | 45 | 53 | 61 | 73 | 91 | 97 | 98.7 |
| 6 | H.L.-8 | 2 | 13 | 23 | 37 | ----- | 45 | 49 | 53 | 61 | 79 | 93 | 97.3 |
| 7 | D.F.C. | ----- | ----- | 0.3 | 20 | 35 | 47 | 71 | 83 | 89 | 93 | 96 | 97.3 |
| 8 | Mod. D.F.C. | ----- | ----- | ----- | 20 | ----- | 55 | 70 | 77 | 81 | 87 | 92 | 95.6 |
| 9 | O.F.C. | ----- | ----- | ----- | 5 | ----- | 65 | 77 | 87 | 92 | 95 | 98 | 98.4 |
| 10 | HL-3R.H.M. | ----- | ----- | 2 | 19 | ----- | 45 | 52 | 58 | 66 | 84 | 93 | 95.3 |
| 11 | H.L.-4 | ----- | 0.3 | 6 | 21 | ----- | 40 | 49 | 59 | 70 | 90 | 93 | 95.3 |

## Table 5 MIX DESIGN DATA

| Mix # | Contract # | A.C. Grade | % A.C. | % Retained 4.75 Sieve | B.R.D. | M.R.D. | Stability(N) | Flow 0.25 mm | %Voids Surface Dry | % V.M.A.. |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | correlation material | 85/100 | 5.1 | 45 | 2.521 | 2.640 | 16700 | 9.2 | 4.1 | 14.9 |
| 2 | 86-45 | 85/100 | 5.4 | 45 | 2.388 | 2.488 | 11500 | 9.0 | 3.0 | 15.7 |
| 3 | correlation material | 85/100 | 5.3 | 45 | 2.412 | 2.547 | 13600 | 10.4 | 4.0 | 13.8 |
| 4 | GGE-311 | 85/100 | 4.8 | 45 | 2.394 | 2.492 | 10200 | 8.5 | 3.0 | 15.1 |
| 5 | correlation material | 85/100 | 5.3 | 45 | 2.408 | 2.530 | 10300 | 7.9 | 4.0 | 15.7 |
| 6 | 86-59 | 85/100 | 5.5 | 45 | 2.358 | 2.466 | 9100 | 8.0 | 3.0 | 16.2 |
| 7 | 84-67 | 85/100 | 5.6 | 45 | 2.971 | 3.066 | 16200 | 14.4 | 1.6 | 13.5 |
| 8 | 85-64 | 85/100 | 4.7 | 55 | 2.426 | 2.491 | 14800 | 13.5 | 2.3* | 13.8 |
| 9 | 85-77 | 85/100 | 5.2 | 65 | 2.832 | 3.018 | 11800 | 11.7 | 5.3 | 16.2 |
| 10 | 86-38 | 300/400 | 5.2 | 45 | 2.396 | 2.513 | 10200 | 9.6 | 3.7 | 15.4 |
| 11 | 86-202 | 150/200 | 5.2 | 40 | 2.420 | 2.510 | 10100 | 11.2 | 2.5 | 15.2 |

* corrected for absorption

## Table 6 FIELD SAMPLE PROPERTIES

| Mix Type | %A.C. | Marshall Recompaction | | | Pavement Sample | | | % Retained Cumulative | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | mm | | | | | | | µm | | | |
| | | % Voids | Flow | Stab. | % Voids | % Comp. | Lift | 16.0 | 13.2 | 9.5 | 6.7 | 4.75 | 2.36 | 1.18 | 600 | 300 | 150 | 75 |
| **Hwy. 401, Port Hope** | | | | | | | | | | | | | | | | | | |
| H.L. - 4 | 4.70 | 2.5 | 12.2 | 11530 | 3.9 | 98.5 | B | --- | 5 | 23 | 35 | 43 | 54 | 64 | 73 | 84 | 95 | 97.3 |
| **Hwy. 401, Trench 'A'** | | | | | | | | | | | | | | | | | | |
| H.L. - 1 | 4.93 | 2.6 | 13.8 | 18450 | 3.4 | 99.2 | S | --- | --- | 15 | 34 | 46 | 58 | 67 | 79 | 89 | 96 | 97.6 |
| H.L. - 4 | 5.30 | 2.7 | 13.3 | 14370 | 3.7 | 99.0 | B | 1 | 4 | 20 | 31 | 39 | 50 | 61 | 73 | 85 | 95 | 97.4 |
| **Hwy. 401, Trench 'B'** | | | | | | | | | | | | | | | | | | |
| H.L. - 1 | 5.19 | 2.4 | 14.2 | 16960 | 3.3 | 99.2 | S | --- | --- | 14 | 33 | 46 | 57 | 63 | 69 | 84 | 94 | 96.4 |
| H.L. - 4 | 5.22 | 3.1 | 11.8 | 12490 | 4.2 | 98.9 | B | 1 | 4 | 20 | 34 | 42 | 51 | 58 | 65 | 82 | 93 | 95.7 |
| **Bloomington Road** | | | | | | | | | | | | | | | | | | |
| H.L. - 3 | 6.20 | 1.5 | 25+ | 5576 | 3.3 | 98.2 | S | --- | --- | 11 | 26 | 34 | 46 | 57 | 70 | 84 | 92 | 95.9 |
| H.L. - 8 | 6.60 | 1.7 | 25+ | 8220 | 4.4 | 97.3 | B | 8 | 14 | 25 | 36 | 43 | 53 | 62 | 74 | 89 | 96 | 97.8 |

B = Binder Course
S = Surface Course

## Table 7 BEAM TOP LIFT DENSITY DATA BEFORE AND AFTER TESTING FOR DIFFERENT INITIAL TEMPERATURES

| Mix# - Mix Type | BEFORE TESTING | | | | WHEEL TRACK DATA AFTER TESTING | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Bulk Relative Density (S.R.D.) | | | | %Compaction of Mix Design B.R.D. | | | | % Voids | | | |
| | Lift Thickness (mm) | B.R.D. | % Compaction | % Voids | 60C | 70C | 85C | 100C | 60C | 70C | 85C | 100C | 60C | 70C | 85C | 100C |
| 1 H.L.-1 | 35.6 | 2.380 | 94.4 | 9.8 | 2.422 | 2.503 | 2.466 | 2.486 | 96.1 | 99.3 | 97.9 | 98.7 | 8.3 | 5.2 | 6.5 | 5.8 |
| 2 H.L.-3 | 36.3 | 2.294 | 96.1 | 7.8 | 2.321 | 2.348 | 2.372 | 2.373 | 97.2 | 98.3 | 99.3 | 99.4 | 6.7 | 5.6 | 4.7 | 4.6 |
| 3 H.L.-4 | 37.4 | 2.300 | 95.4 | 9.7 | 2.347 | 2.334 | 2.351 | 2.371 | 97.3 | 96.8 | 97.5 | 98.3 | 7.9 | 8.4 | 7.7 | 6.9 |
| 4 H.L.-4 | 36.9 | 2.310 | 96.5 | 7.3 | 2.344 | 2.370 | 2.391 | 2.392 | 97.9 | 99.0 | 99.9 | 99.9 | 5.9 | 4.9 | 4.1 | 4.0 |
| 5 H.L.-8 | 38.1 | 2.297 | 95.4 | 9.2 | 2.331 | 2.359 | 2.374 | 2.368 | 96.8 | 98.0 | 98.6 | 98.3 | 7.9 | 6.8 | 6.2 | 6.4 |
| 6 H.L.-8 | 37.6 | 2.318 | 96.3 | 6.4 | 2.334 | 2.364 | 2.387 | 2.399 | 99.0 | 101.1 | 101.2 | 101.7 | 5.4 | 3.3 | 3.2 | 2.7 |
| 7 D.F.C. | 36.0 | 2.704 | 91.0 | 11.8 | ---- | 2.758 | 2.751 | 2.732 | --- | 92.8 | 92.6 | 92.0 | --- | 10.0 | 10.3 | 10.9 |
| 8 Mod. D.F.C. | 39.0 | 2.363 | 97.4 | 5.1 | 2.406 | 2.427 | 2.436 | 2.453 | 99.2 | 100.1 | 100.4 | 101.1 | 3.4 | 2.6 | 2.2 | 1.5 |
| 9 O.F.C. | 37.7 | 2.727 | 96.3 | 9.6 | 2.729 | 2.699* | 2.763 | 2.741 | 96.4 | 95.3* | 98.3 | 96.6 | 9.6 | 10.6* | 7.8 | 9.2 |
| 10 HL-3 R.H.M. | 36.5 | 2.348 | 98.0 | 6.6 | 2.381 | 2.442 | 2.440 | 2.465 | 99.4 | 101.9 | 101.8 | 102.9 | 5.3 | 2.8 | 2.9 | 1.9 |
| 11 H.L.-4 | 36.4 | 2.410 | 99.6 | 4.0 | 2.479 | 2.486 | 2.491 | 2.517 | 102.4 | 102.7 | 102.9 | 104.0 | 1.2 | 1.0 | 0.8 | 0.0 |

* In error

**Table 8 RUT DEPTHS AT DIFFERENT INITIAL TEMPERATURES AND NUMBERS OF PASSES**

| Mix# - Mix Type | Temperature °C | Number of Passes 500 | 1000 | 2000 | 4000 | 8000 |
|---|---|---|---|---|---|---|
| 1 H.L.-1 | 60 | 0.6 | 0.8 | 1.0 | 1.2 | 1.3 |
| | 70 | 1.5 | 2.1 | 2.3 | 2.5 | 2.8 |
| | 85 | 1.7 | 2.1 | 2.6 | 2.8 | 3.2 |
| | 100 | 3.2 | 3.4 | 4.2 | 4.6 | 5.0 |
| 2 H.L.-3 | 60 | 1.2 | 1.5 | 2.0 | 2.8 | 3.3 |
| | 70 | 2.0 | 2.6 | 3.2 | 3.9 | 4.4 |
| | 85 | 4.2 | 4.9 | 5.1 | 6.0 | 6.2 |
| | 100 | 6.4 | 7.3 | 7.9 | 8.2 | 9.1 |
| 3 H.L.-4 | 60 | 0.8 | 0.9 | 1.3 | 1.7 | 1.8 |
| | 70 | 1.8 | 2.2 | 3.0 | 3.3 | 3.6 |
| | 85 | 2.9 | 4.5 | 4.7 | 4.8 | 5.0 |
| | 100 | 5.0 | 6.3 | 6.6 | 6.8 | 6.9 |
| 4 H.L.-4 | 60 | 2.3 | 2.5 | 3.4 | 3.7 | 5.2 |
| | 70 | 2.9 | 3.8 | 4.7 | 5.0 | 5.3 |
| | 85 | 4.7 | 6.3 | 7.2 | 7.6 | 8.1 |
| | 100 | 6.6 | 8.6 | 10.1 | 10.4 | 10.6 |
| 5 H.L.-8 | 60 | 1.6 | 1.9 | 2.2 | 3.3 | 4.0 |
| | 70 | 2.3 | 2.4 | 2.9 | 3.1 | 3.6 |
| | 85 | 3.1 | 4.0 | 4.4 | 4.8 | 5.0 |
| | 100 | 6.2 | 6.8 | 8.3 | 8.6 | 9.1 |
| 6 H.L.-8 | 60 | 1.7 | 1.7 | 2.6 | 4.3 | 5.2 |
| | 70 | 3.7 | 4.7 | 5.2 | 6.8 | 7.8 |
| | 85 | 5.8 | 8.2 | 9.1 | 9.6 | 10.6 |
| | 100 | 9.6 | 11.7 | 15.3 | 15.8 | 17.4 |
| 7 D.F.C. | 60 | 0.2 | 0.3 | 0.7 | 1.0 | 1.2 |
| | 70 | 1.1 | 1.3 | 1.4 | 1.8 | 2.2 |
| | 85 | 1.8 | 2.2 | 2.4 | 2.7 | 3.2 |
| | 100 | 2.2 | 2.8 | 3.6 | 4.1 | 4.7 |
| 8 Mod. D.F.C. | 60 | 0.8 | 1.4 | 1.6 | 2.5 | 3.4 |
| | 70 | 2.2 | 3.0 | 3.9 | 4.1 | 4.9 |
| | 85 | 2.9 | 3.8 | 4.7 | 5.4 | 6.1 |
| | 100 | 4.5 | 6.1 | 7.1 | 7.6 | 7.8 |
| 9 O.F.C. | 60 | 1.0 | 1.9 | 2.0 | 2.3 | 3.8 |
| | 70 | 2.2 | 3.0 | 3.9 | 4.1 | 4.9 |
| | 85 | 2.8 | 3.9 | 4.3 | 5.1 | 5.3 |
| | 100 | 4.5 | 5.3 | 6.6 | 7.4 | 8.0 |
| 10 HL-3 R.H.M. | 60 | 1.0 | 2.0 | 2.5 | 4.0 | 4.8 |
| | 70 | 3.0 | 4.0 | 5.0 | 6.0 | 6.5 |
| | 85 | 5.0 | 7.1 | 9.3 | 10.5 | 11.2 |
| | 100 | 6.8 | 9.9 | 13.0 | 14.7 | 16.5 |
| 11 H.L.-4 | 60 | 2.8 | 3.6 | 4.5 | 5.7 | 7.3 |
| | 70 | 3.3 | 4.2 | 5.5 | 7.3 | 8.8 |
| | 85 | 5.4 | 6.6 | 8.4 | 10.2 | 11.7 |
| | 100 | 5.8 | 8.1 | 10.2 | 12.7 | 14.4 |

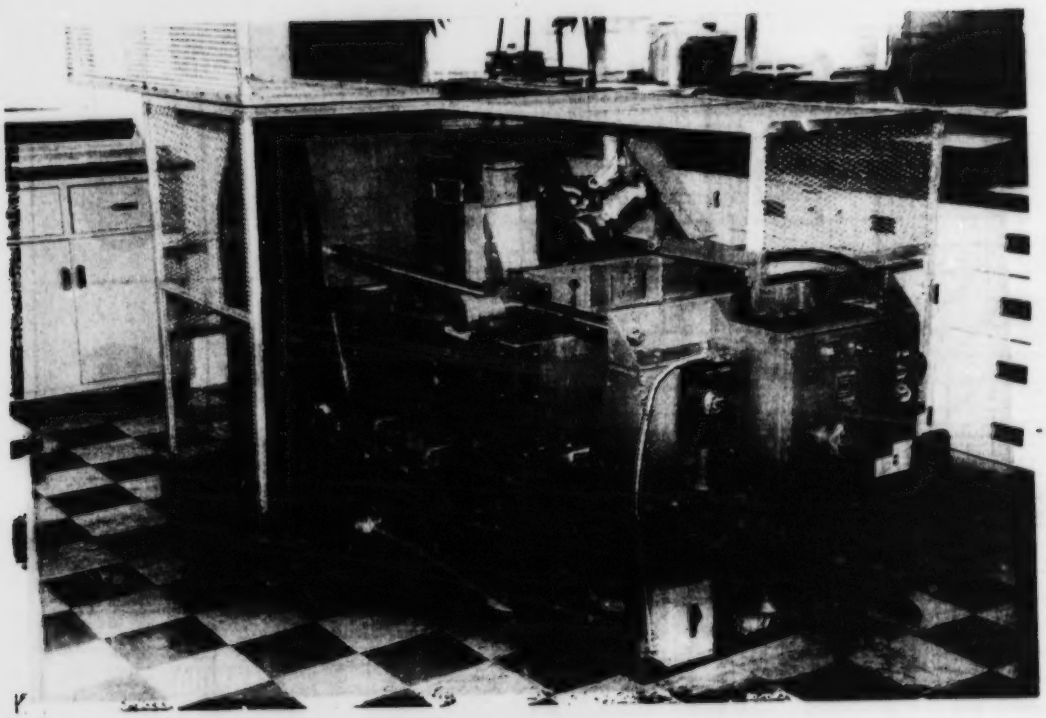


**Fig. 1 Wheel Tracking Machine (W.T.M.)**

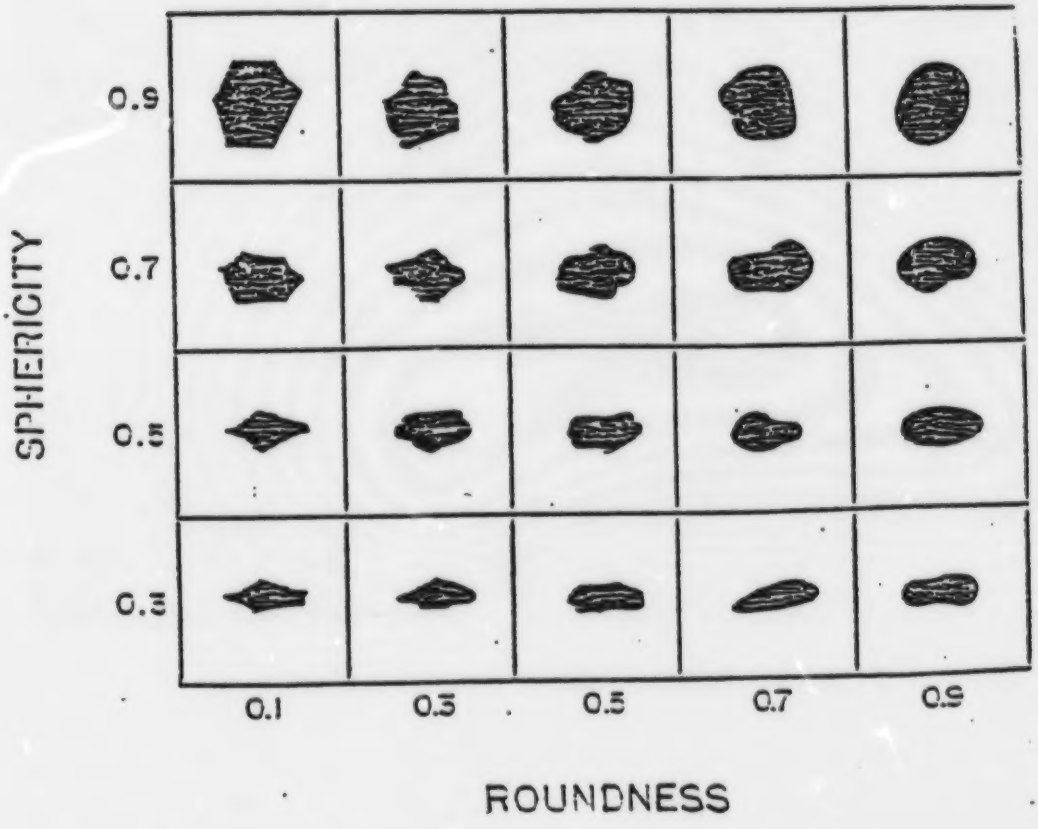
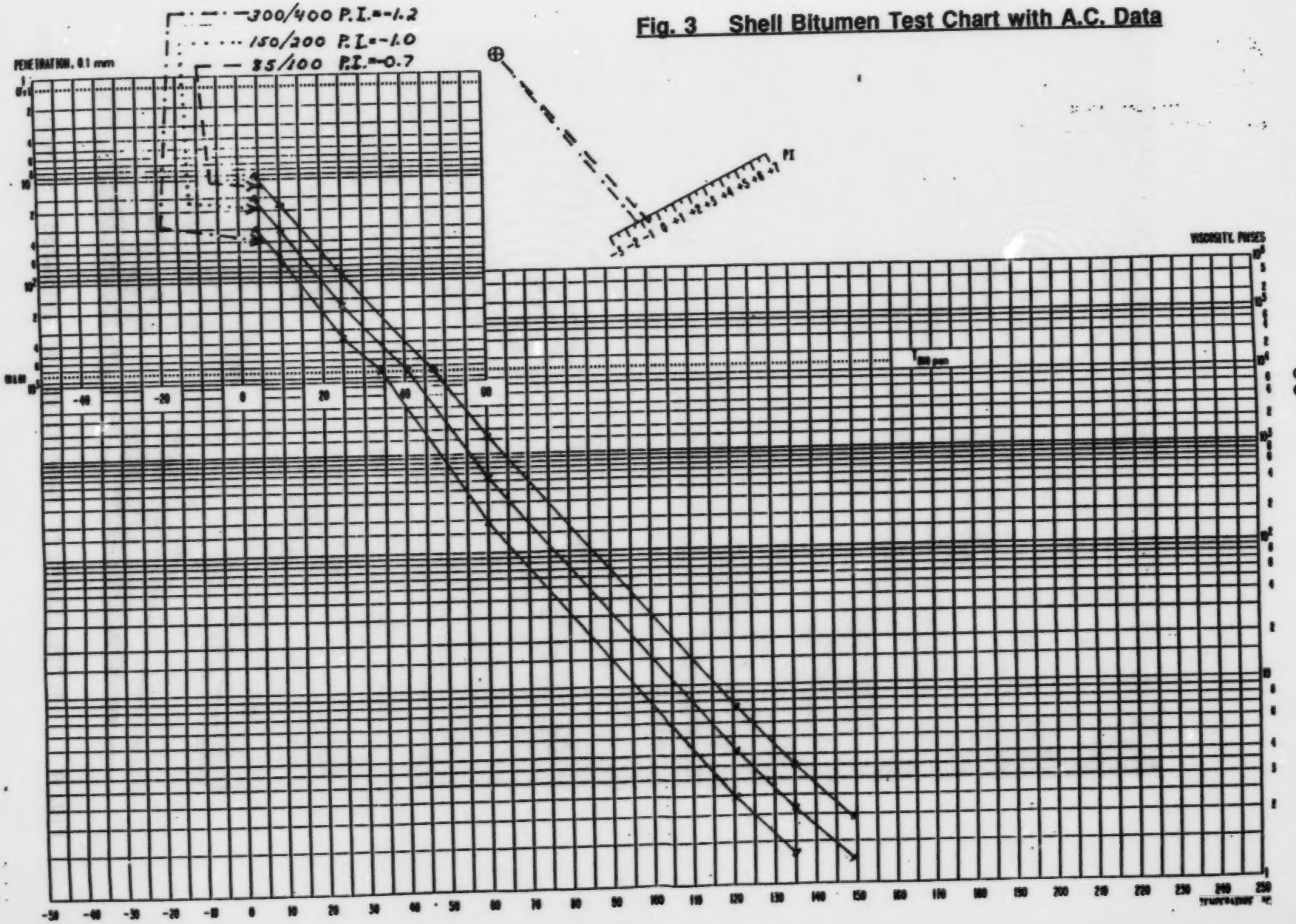
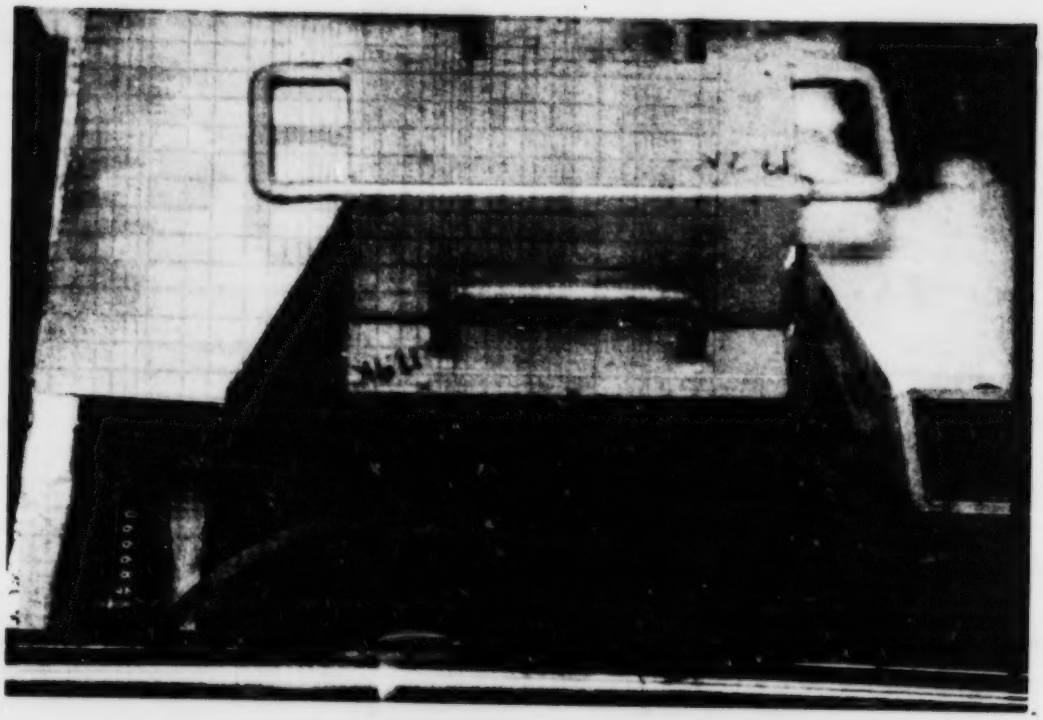



**Fig. 2 Roundness Sphericity Comparison Chart**

**Fig. 3 Shell Bitumen Test Chart with A.C. Data**



a)



b)

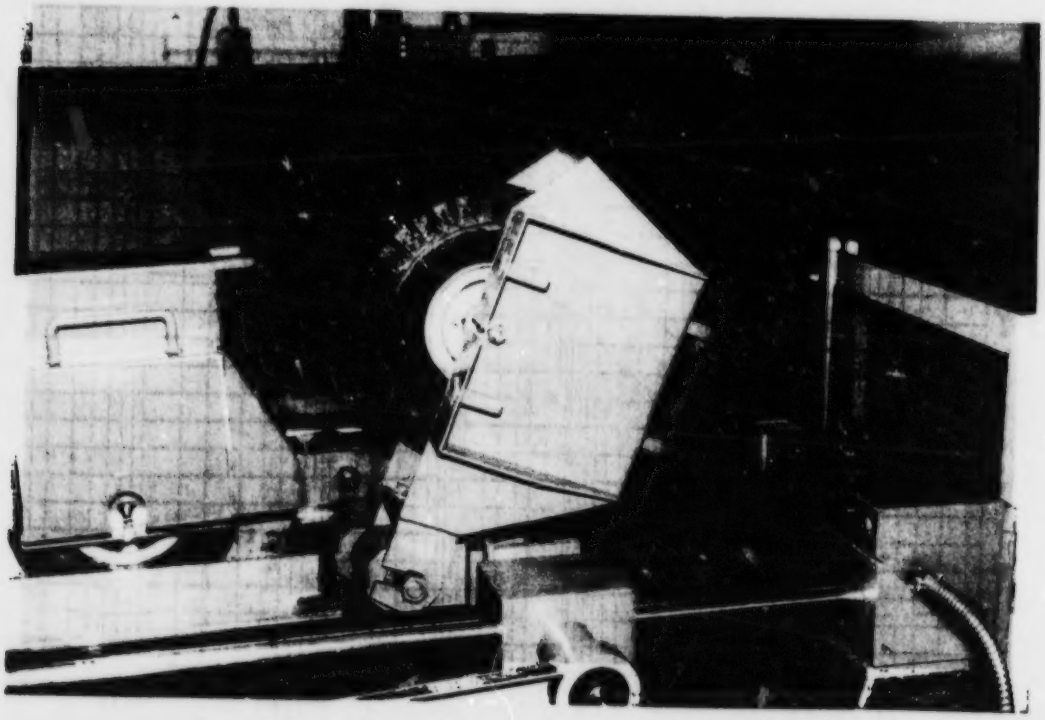


Fig. 4 Wheel Carriage Assembly: a) unloaded b) fully loaded

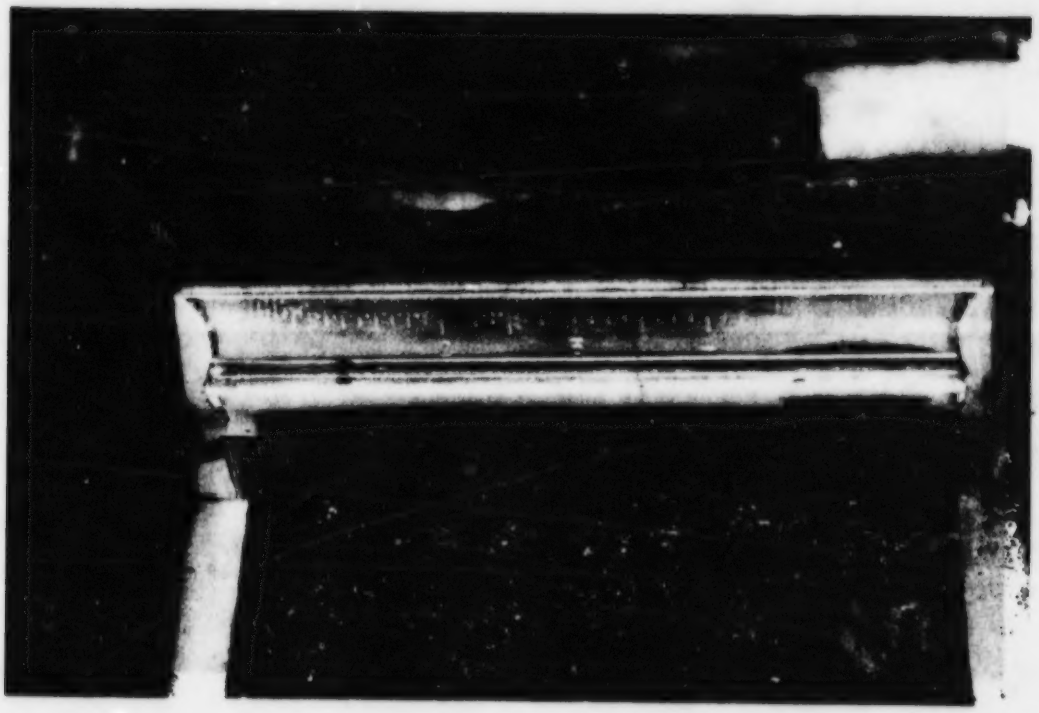


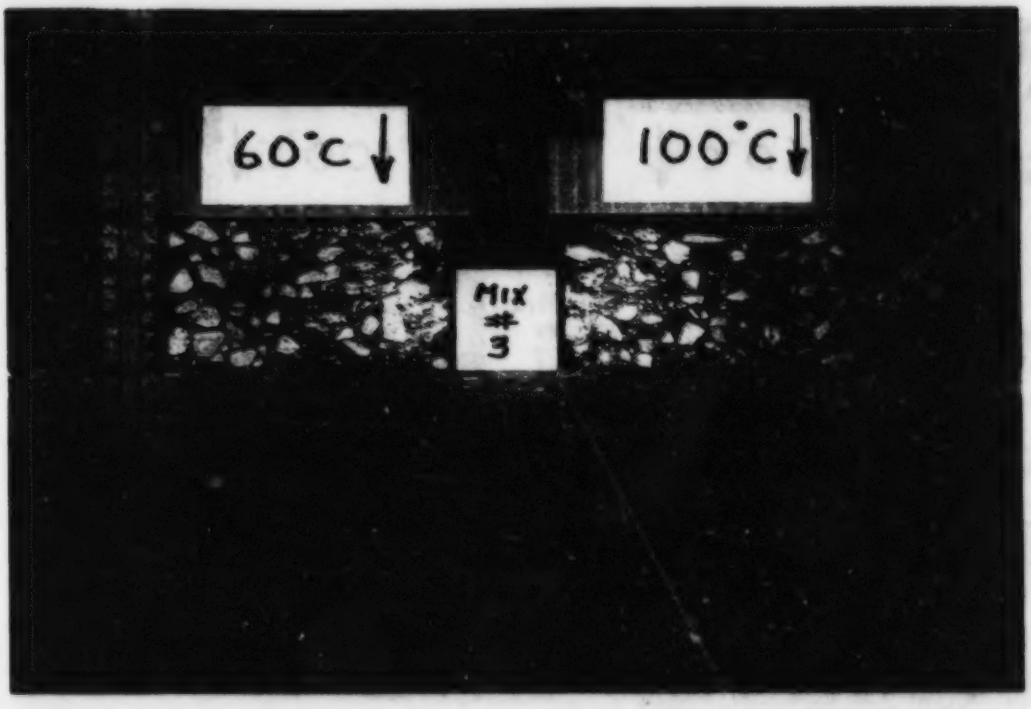
Fig. 5 Rut Depth Measurement by Profilometer

a)

b)

Fig. 6 Sample Cross-sections of Mixes #1, 2, and 10

a)




b)

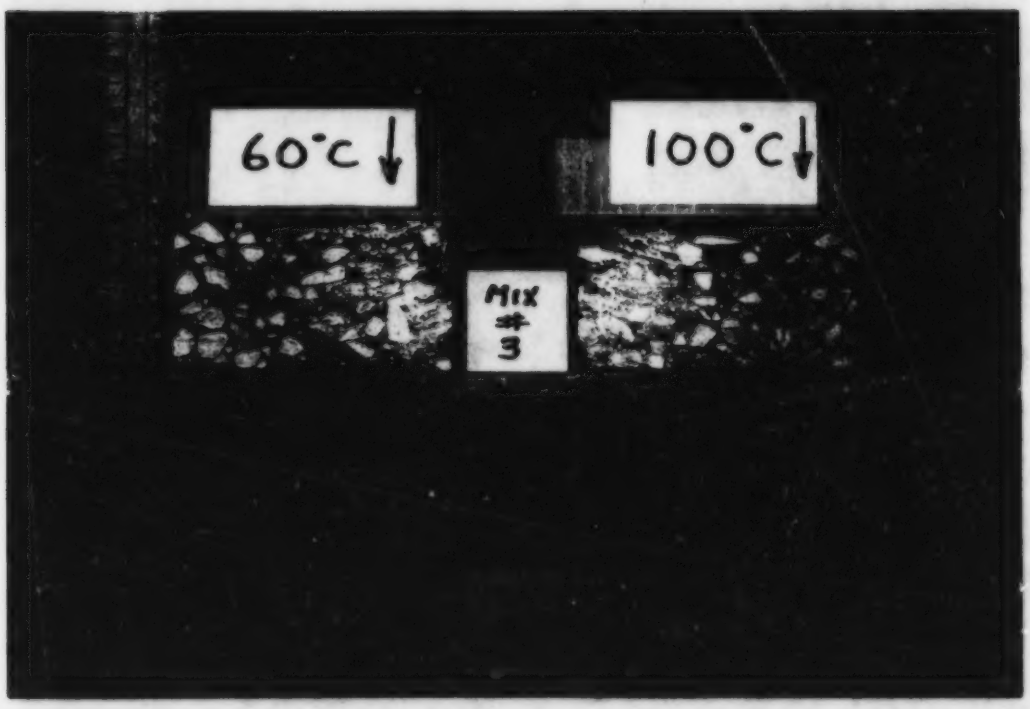
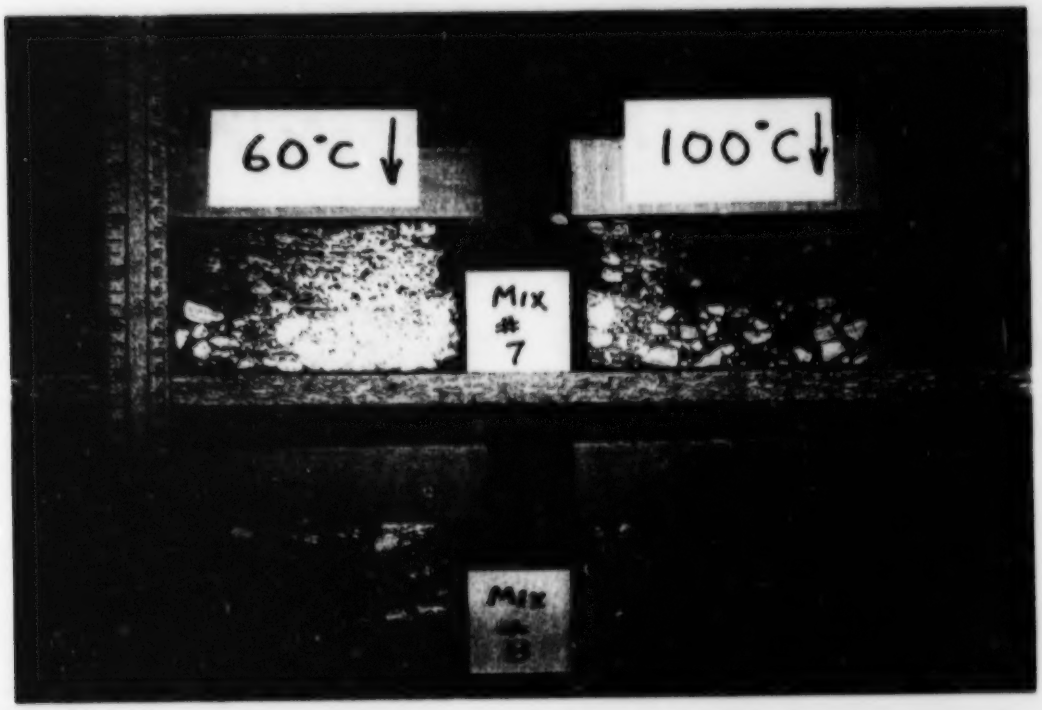



Fig. 7 Sample Cross-sections of Mixes #3, 4, and 11

a)




b)

Fig. 8 Sample Cross-sections of Mixes #7, 8, and 9

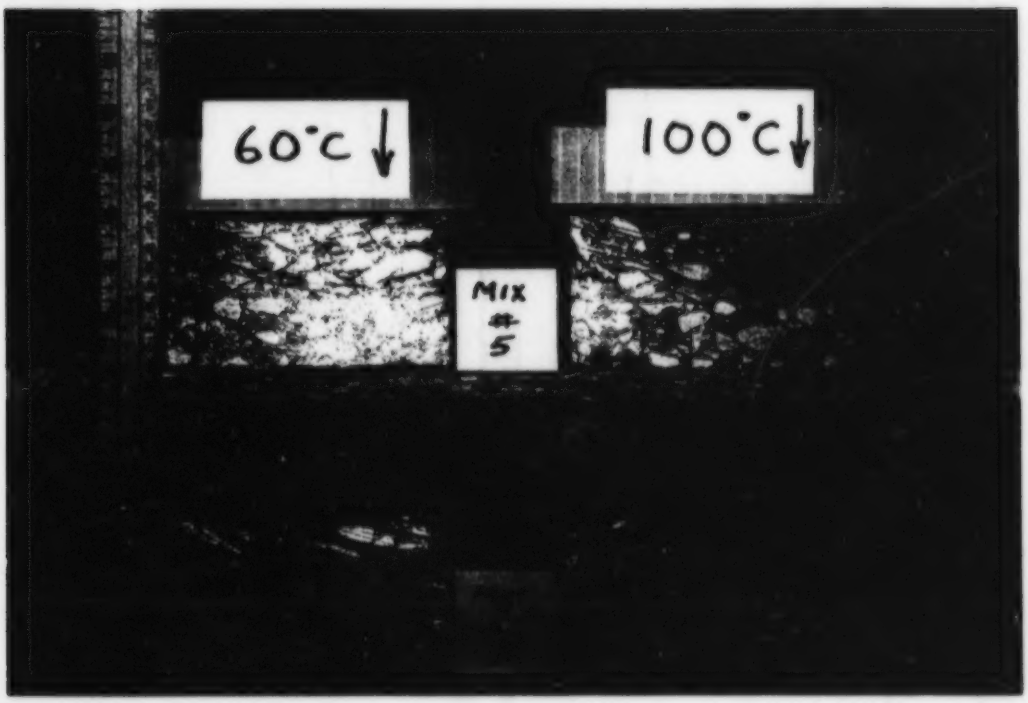



Fig. 9 Sample Cross-sections of Mixes #5 and 6

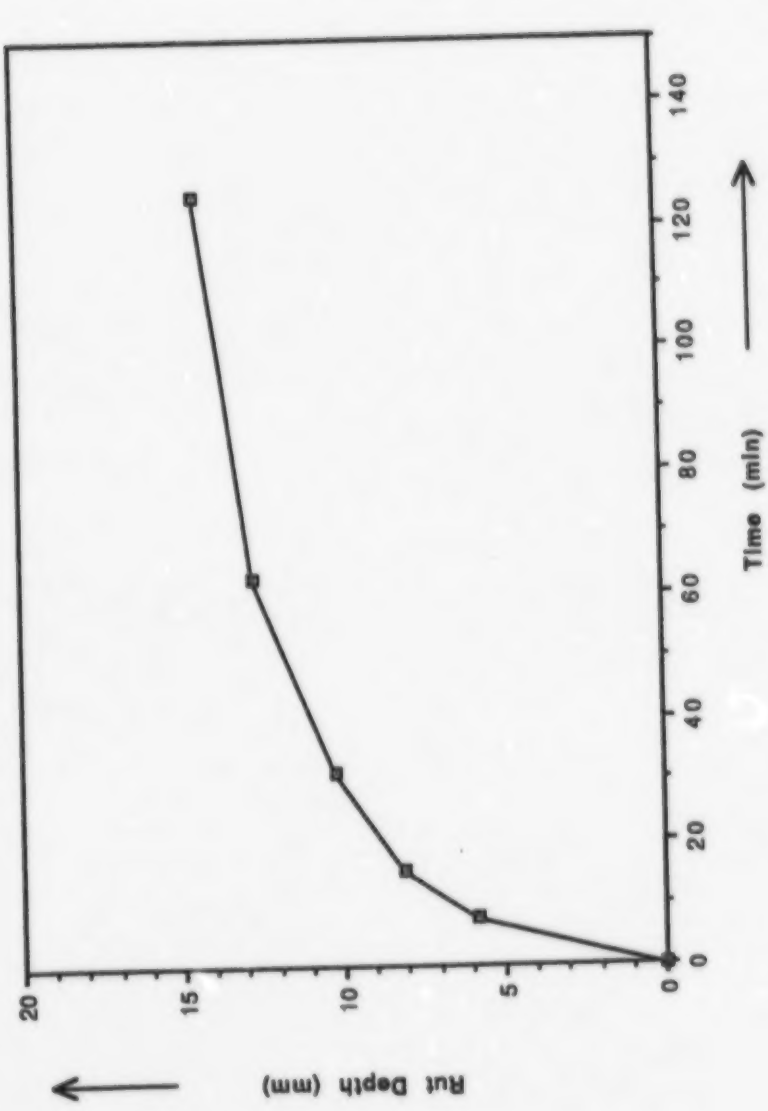



Fig. 10 Typical Deformation (Rut Depth in mm) vs Time (min) Curve

**Fig. 11a Effects of Initial Temperature on Rut Depth with Increasing Passes**

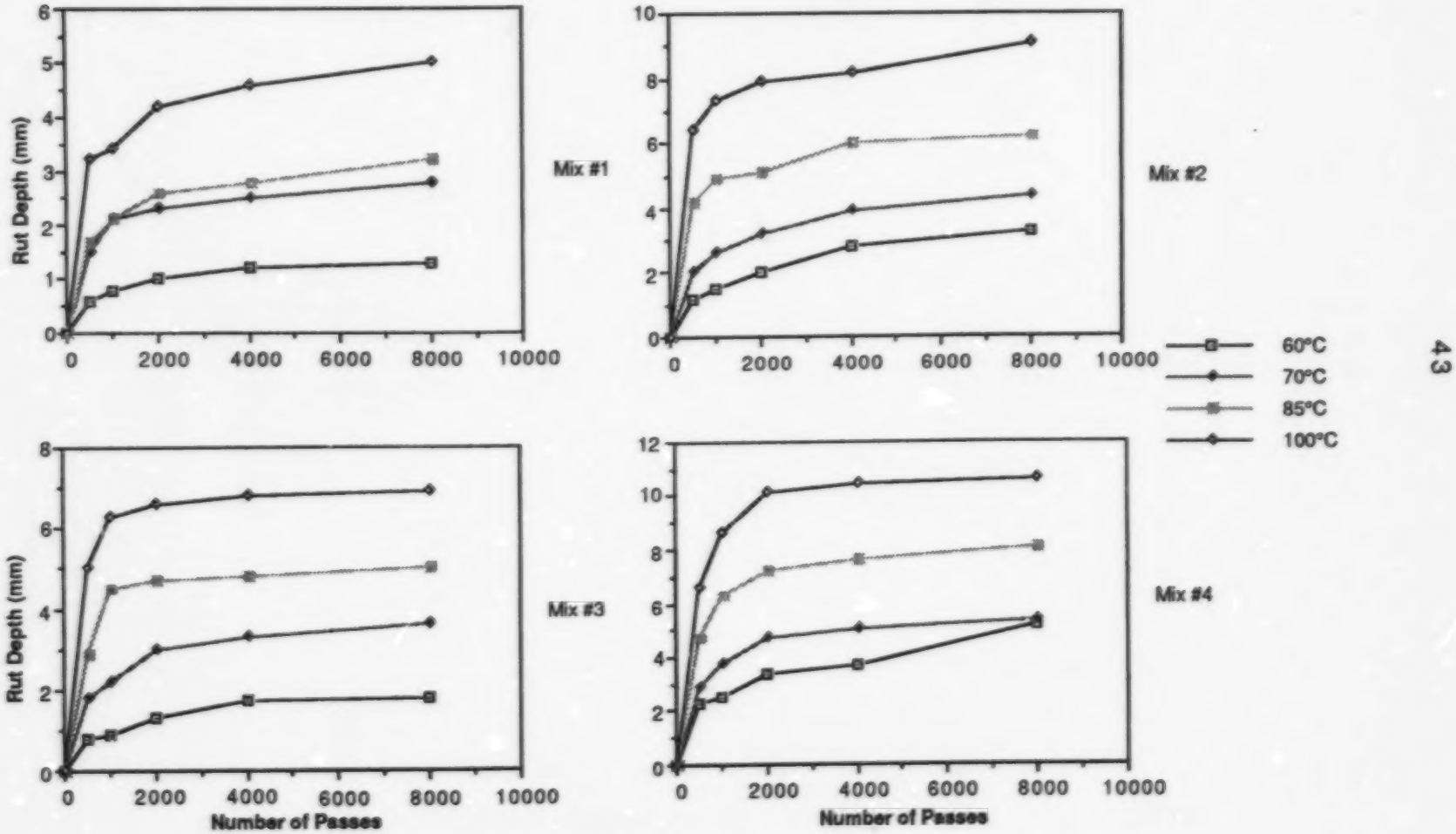
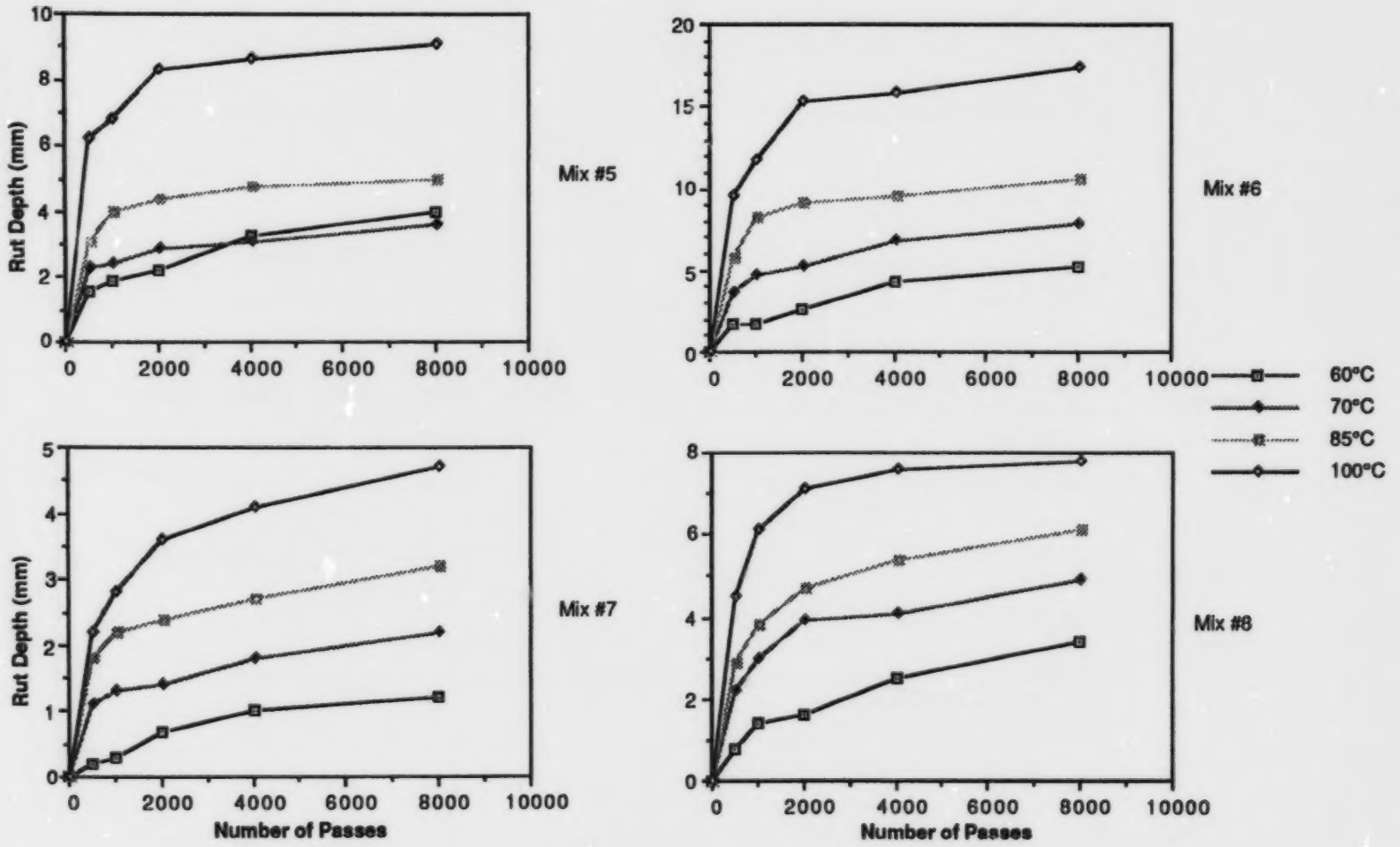
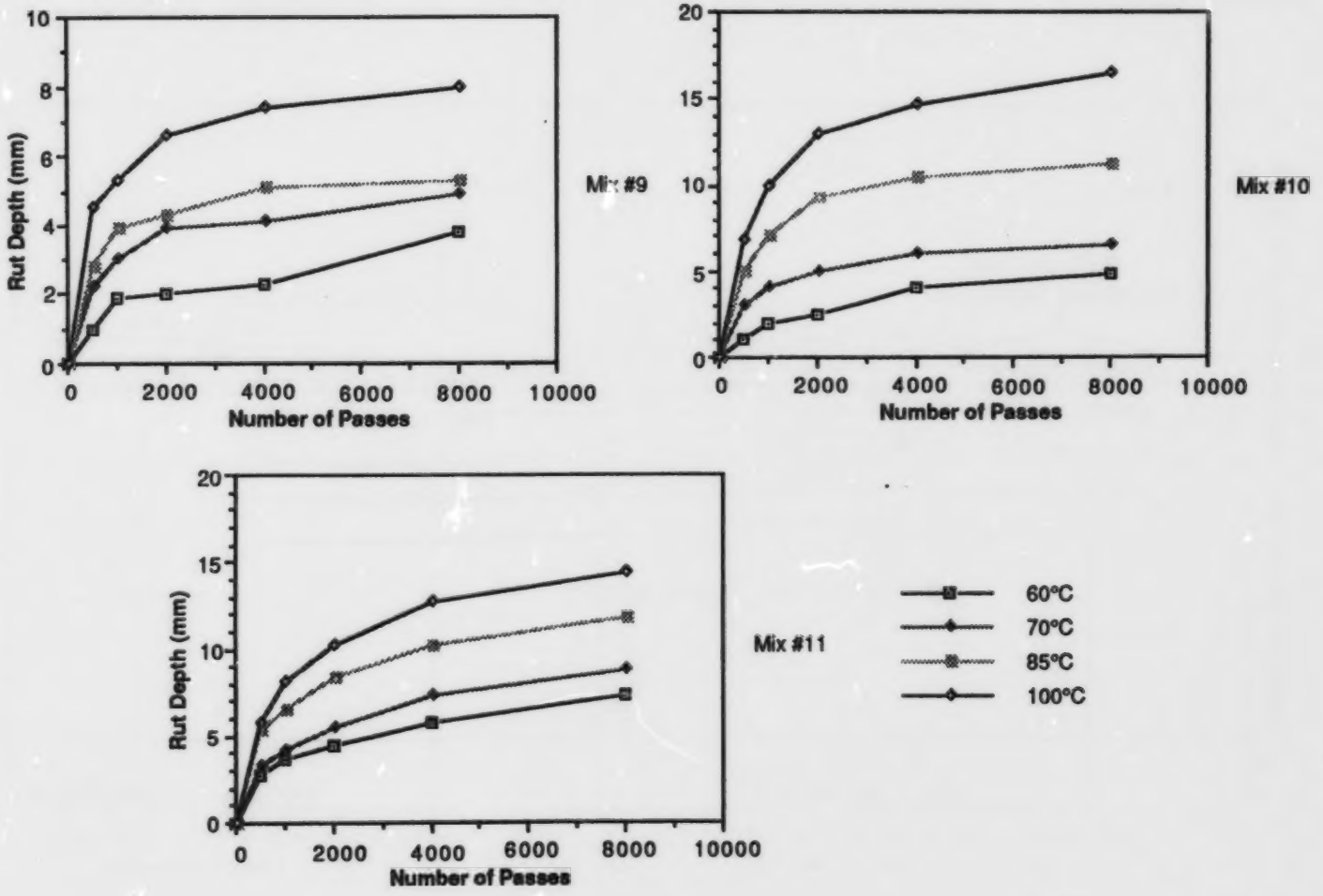


**Fig. 11b Effects of Initial Temperature on Rut Depth with Increasing Passes**



## Fig. 11c Effects of Initial Temperature on Rut Depth with Increasing Passes



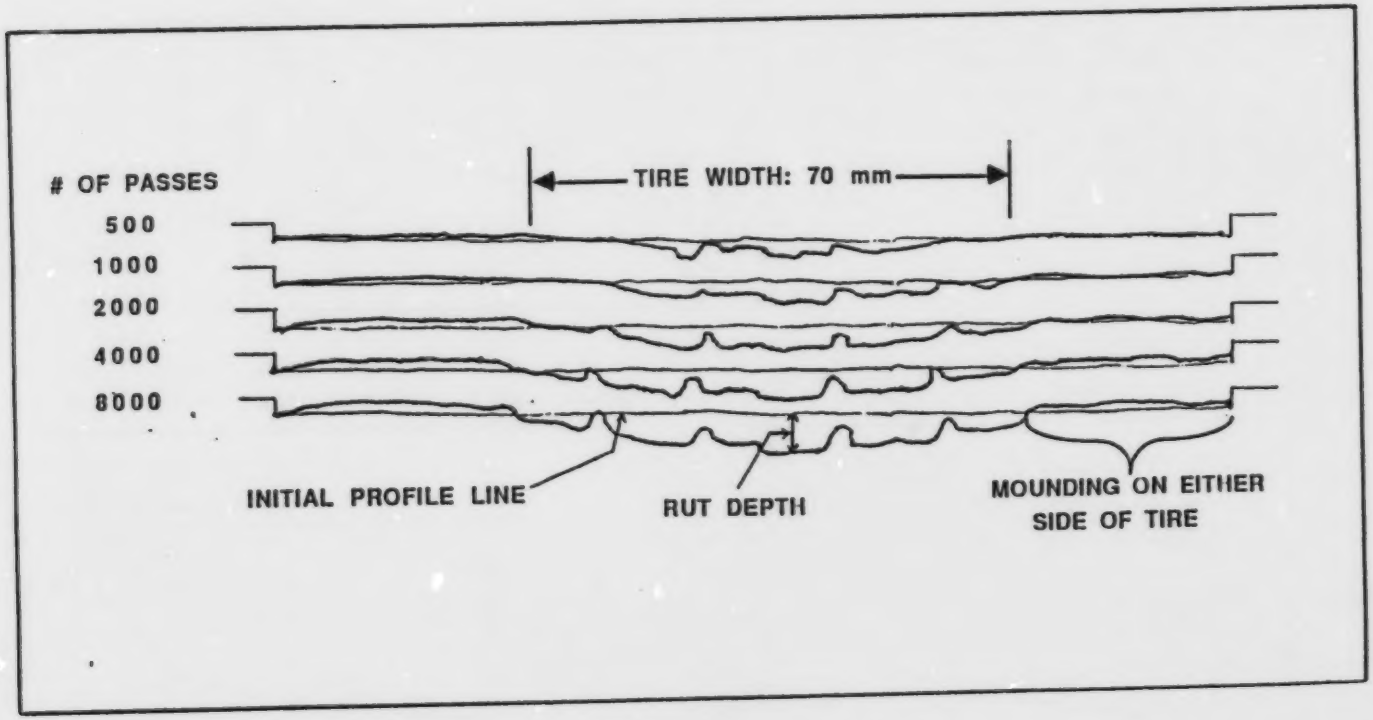
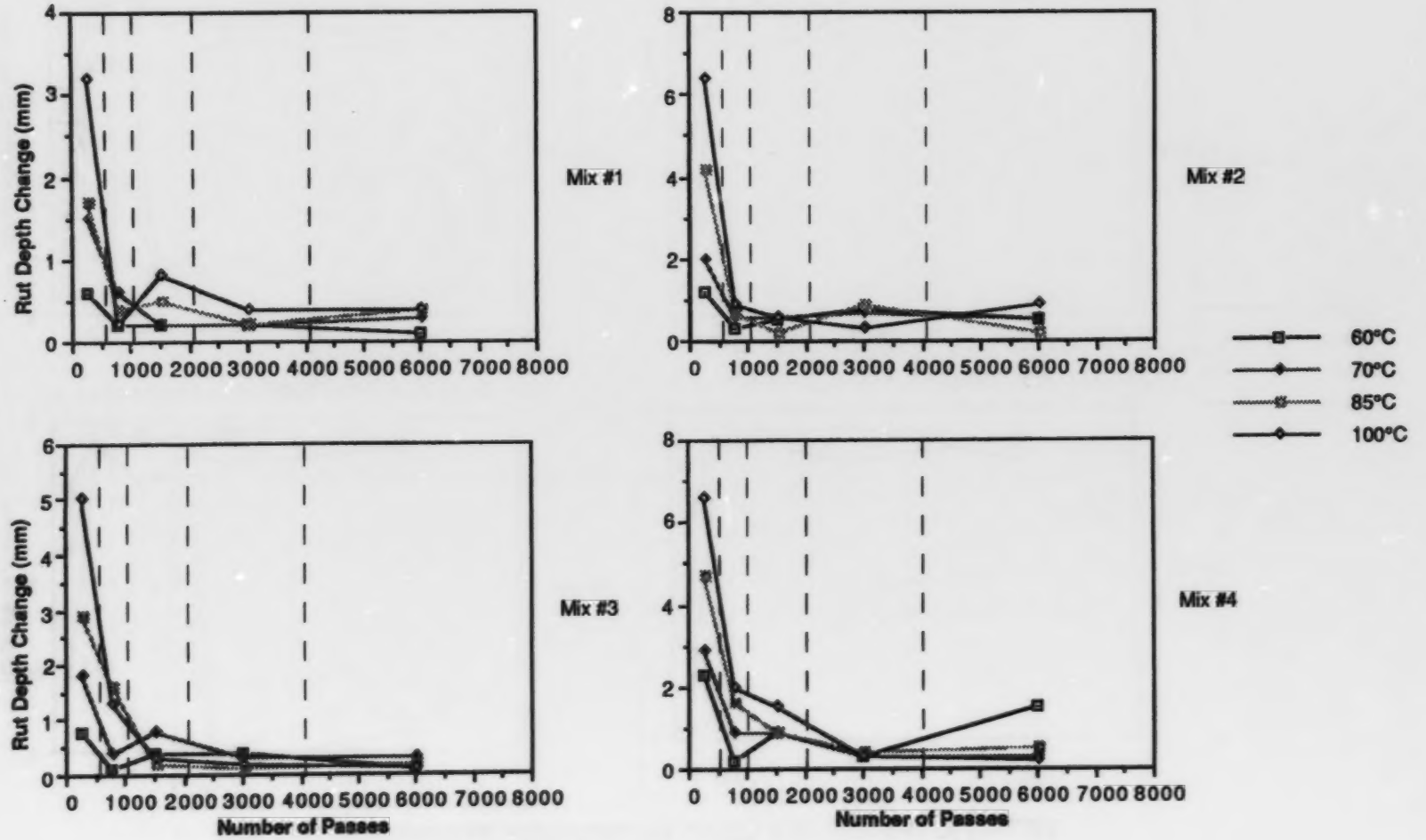
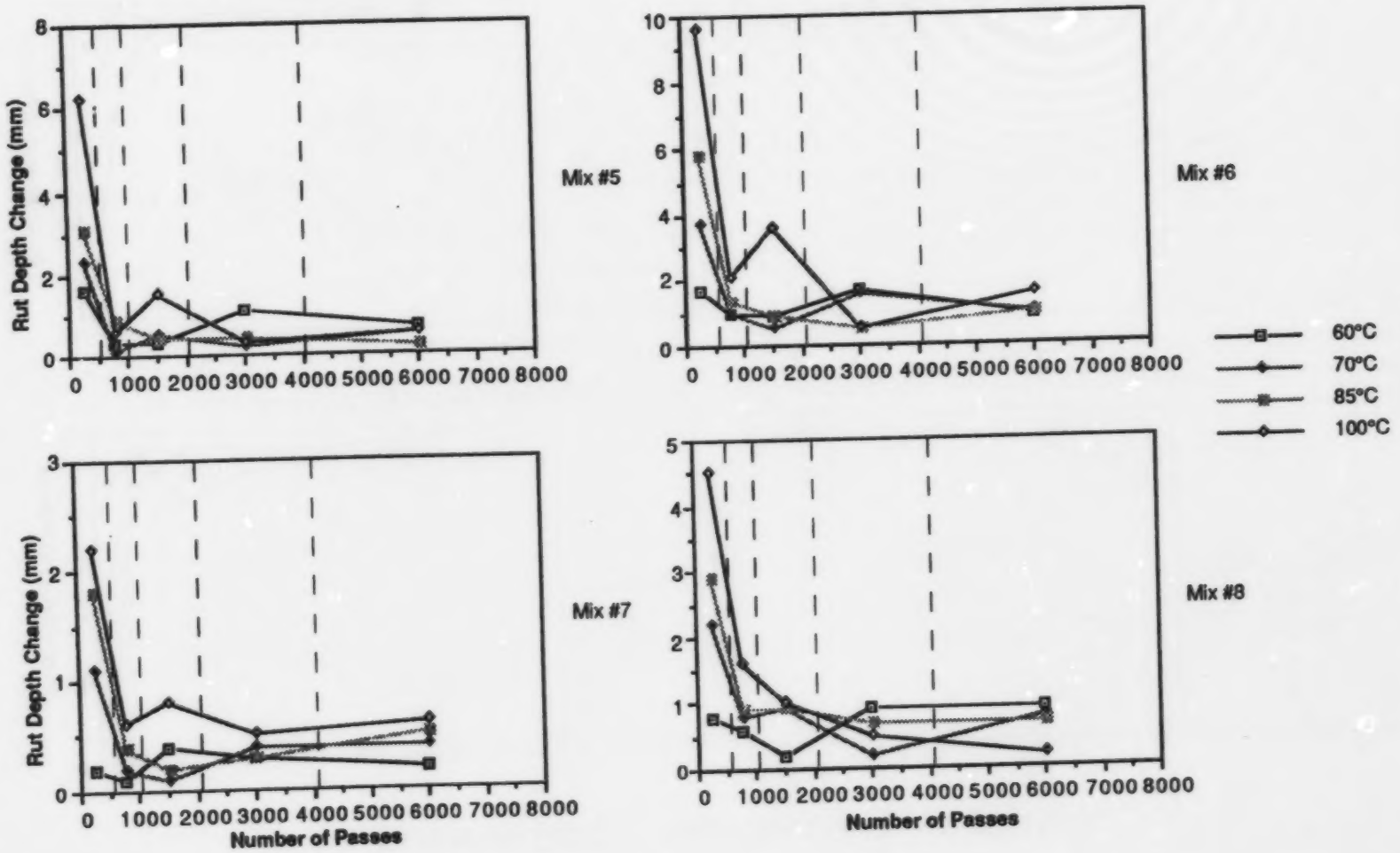



**Fig. 12 Typical Transverse Rut Profile Across the Beam Surface at Different Passes**

## Fig. 13a Incremental Change in Rut Depth with Number of Passes



## Fig. 13b Incremental Change in Rut Depth with Number of Passes



## Fig. 13c Incremental Change in Rut Depth with Number of Passes

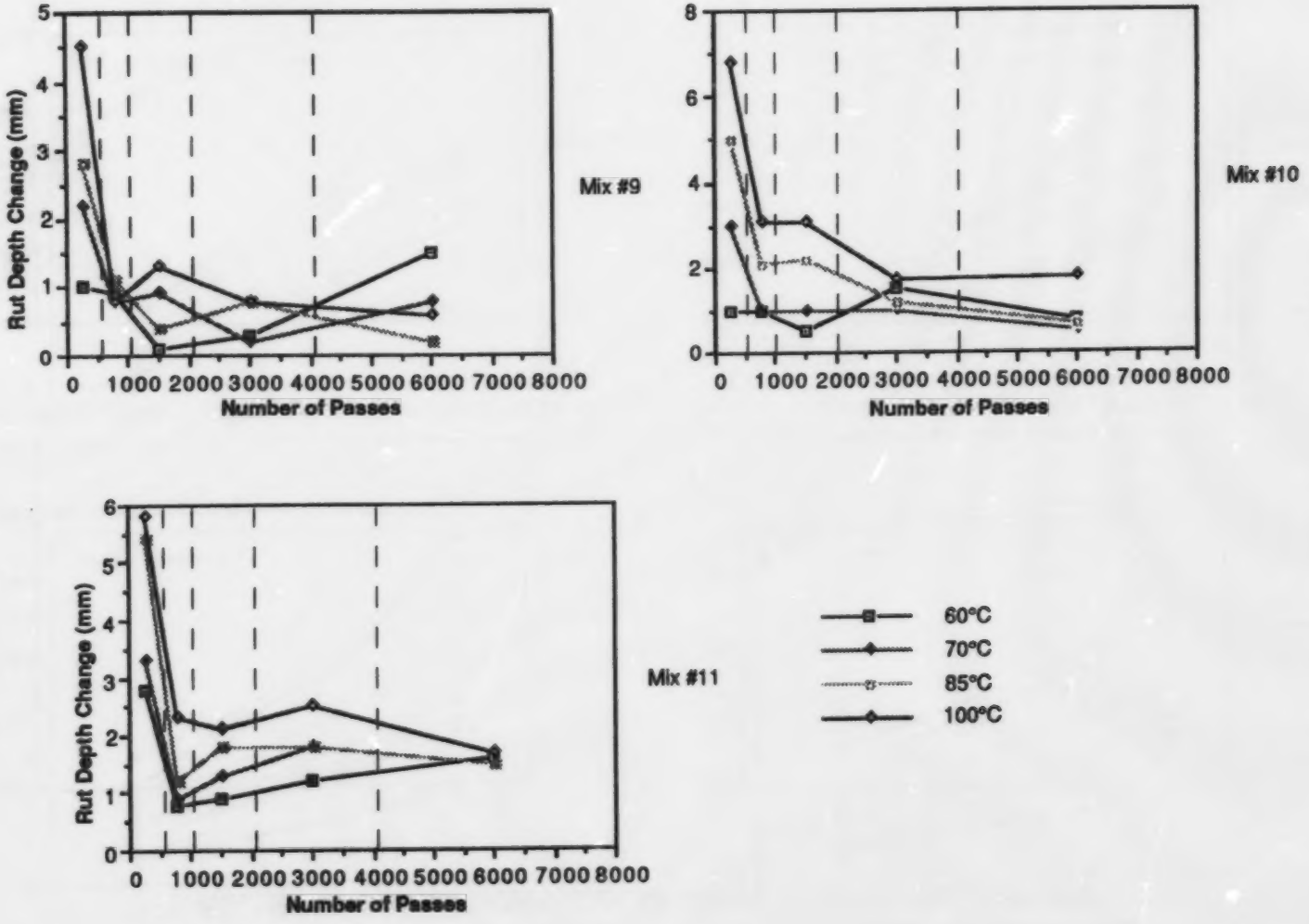
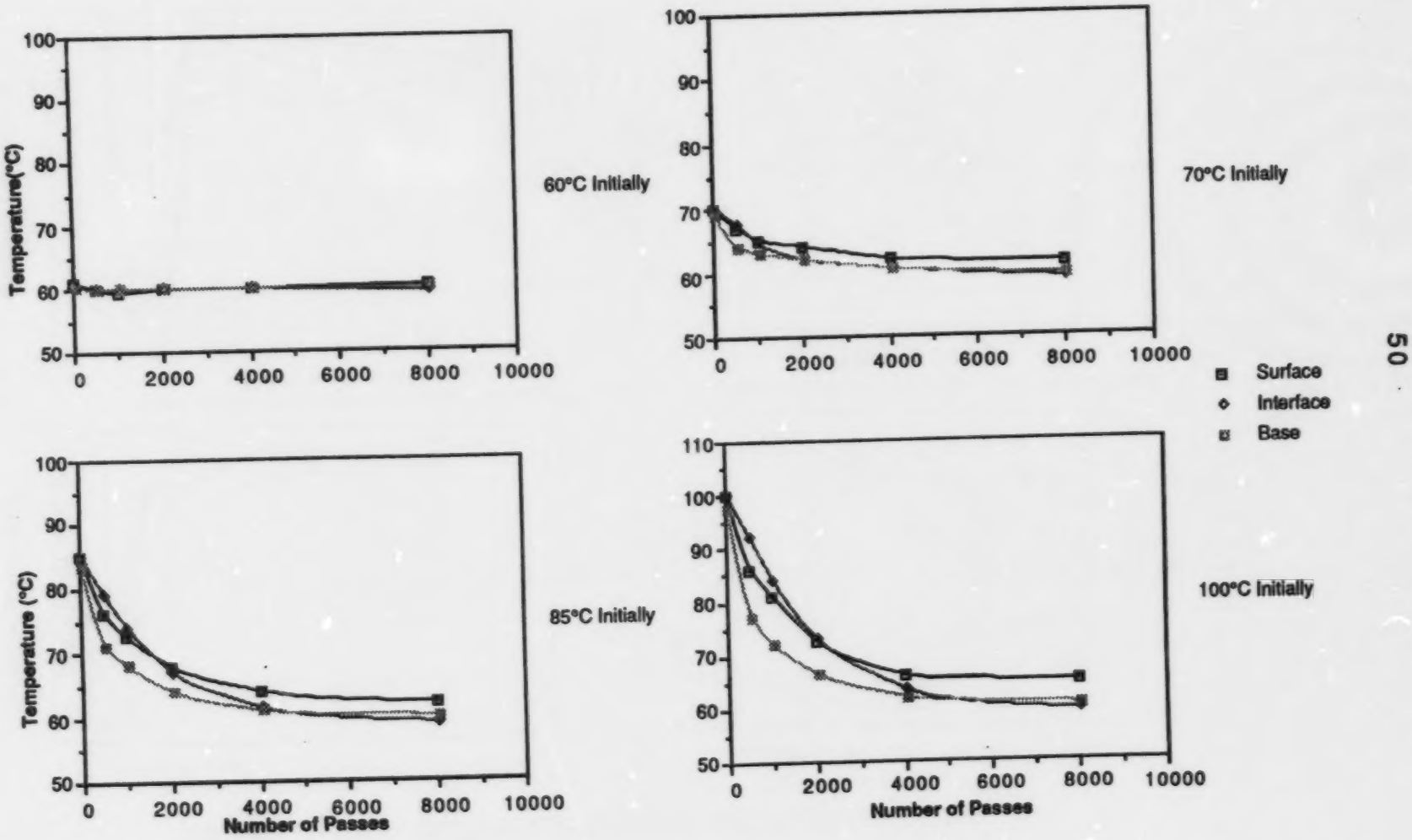


**Fig. 14 Change in Temperature Gradients with Number of Passes**



## Fig. 15 Mix Effect on Rutting at Different Temperatures

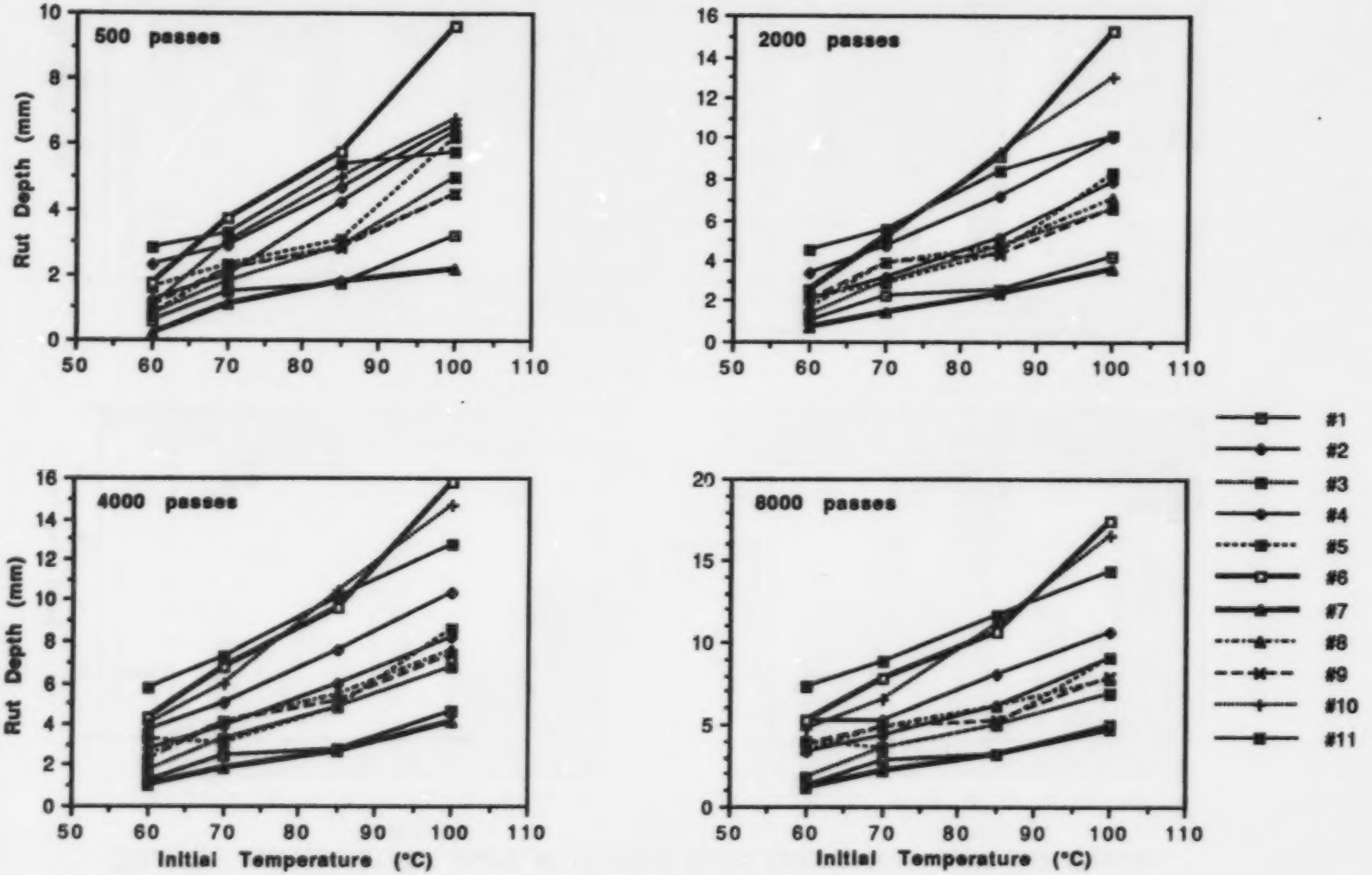


Fig. 16a Variation in Rut Depth at Different Initial Temperatures after 500 Passes

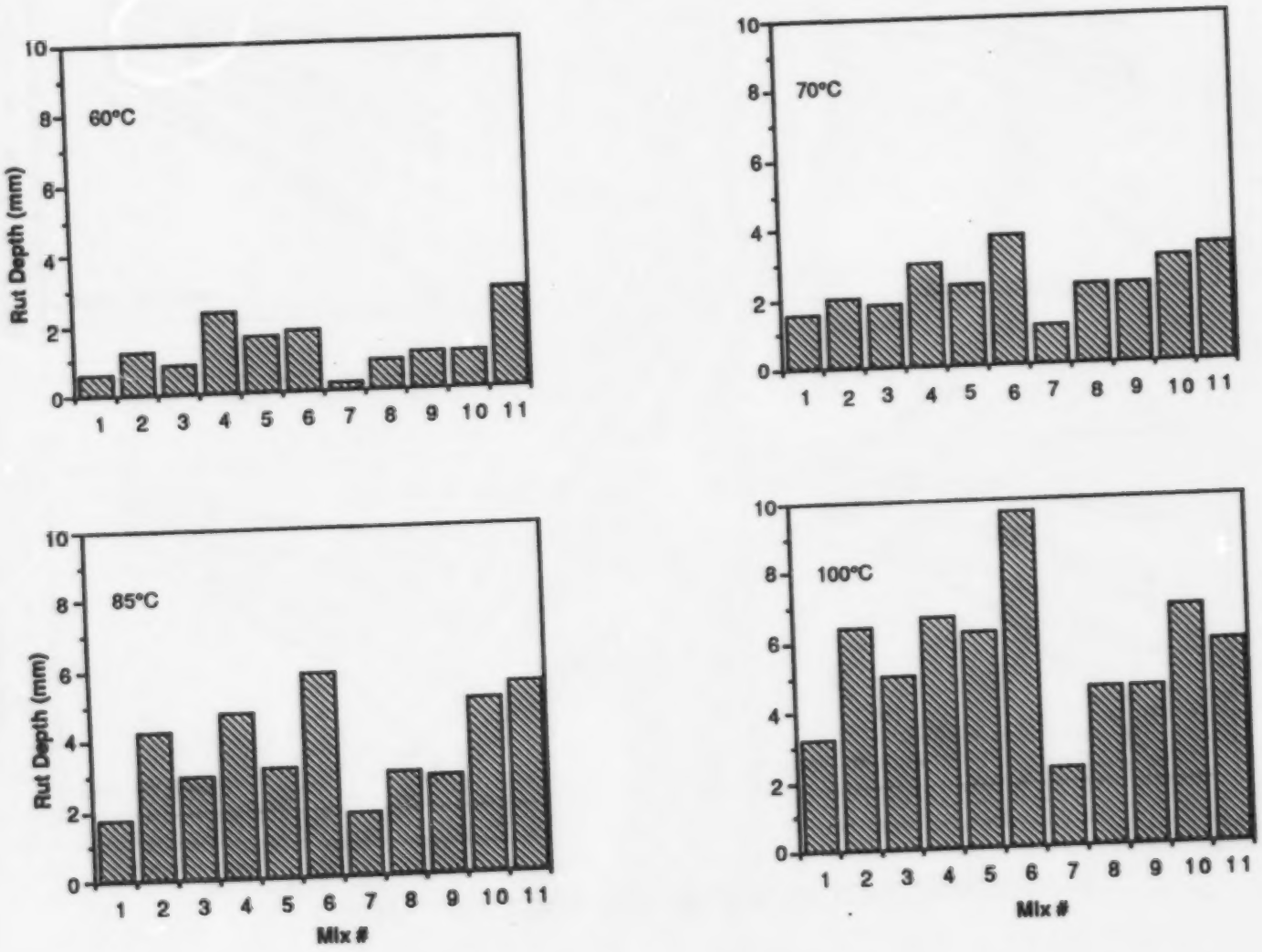


**Fig. 16b Variation in Rut Depth at Different Initial Temperatures after 1000 Passes**

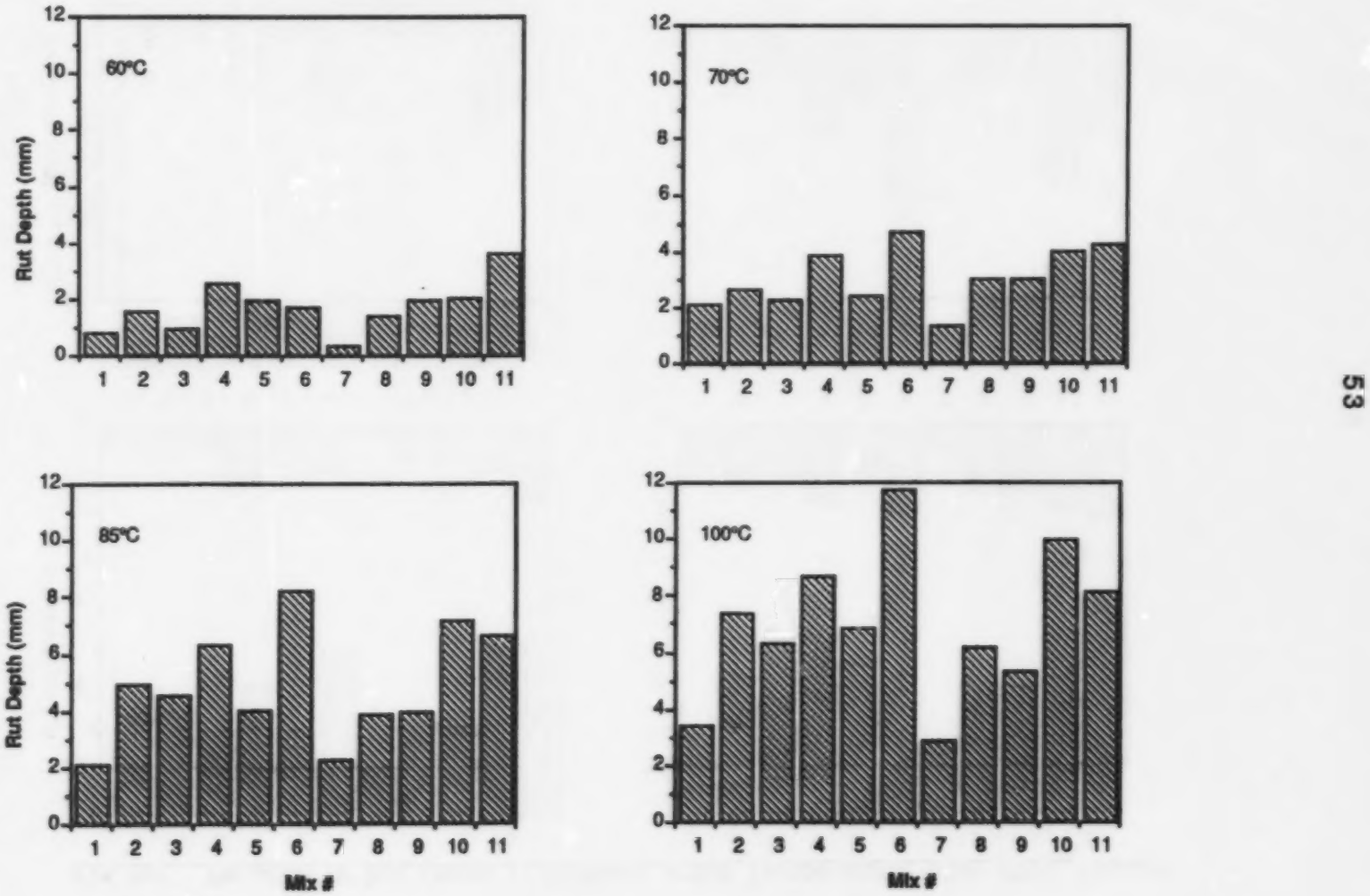


**Fig. 16c Variation in Rut Depth at Different Initial Temperatures after 2000 Passes**

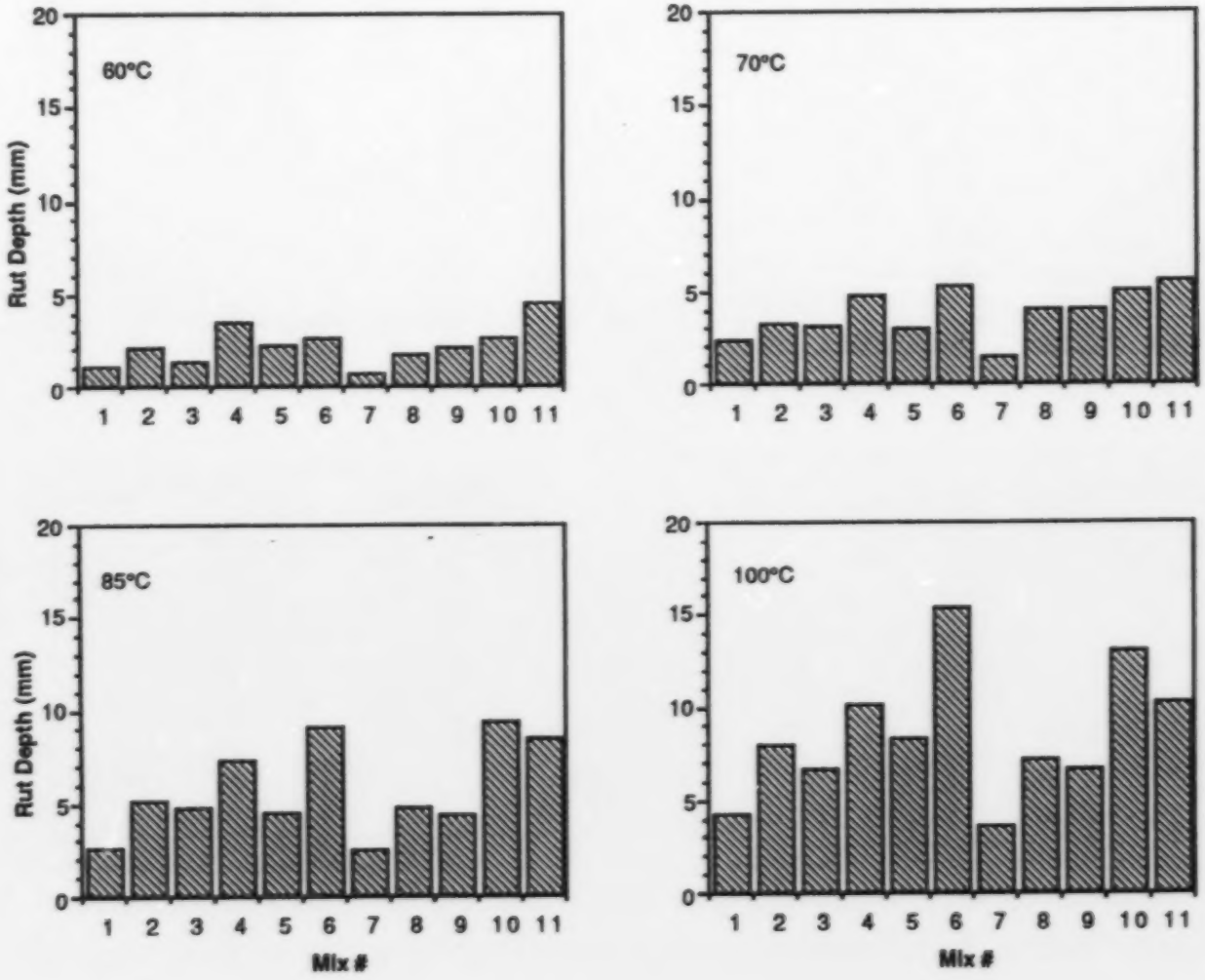


**Fig. 16d Variation in Rut Depth at Different Initial Temperatures after 4000 Passes**

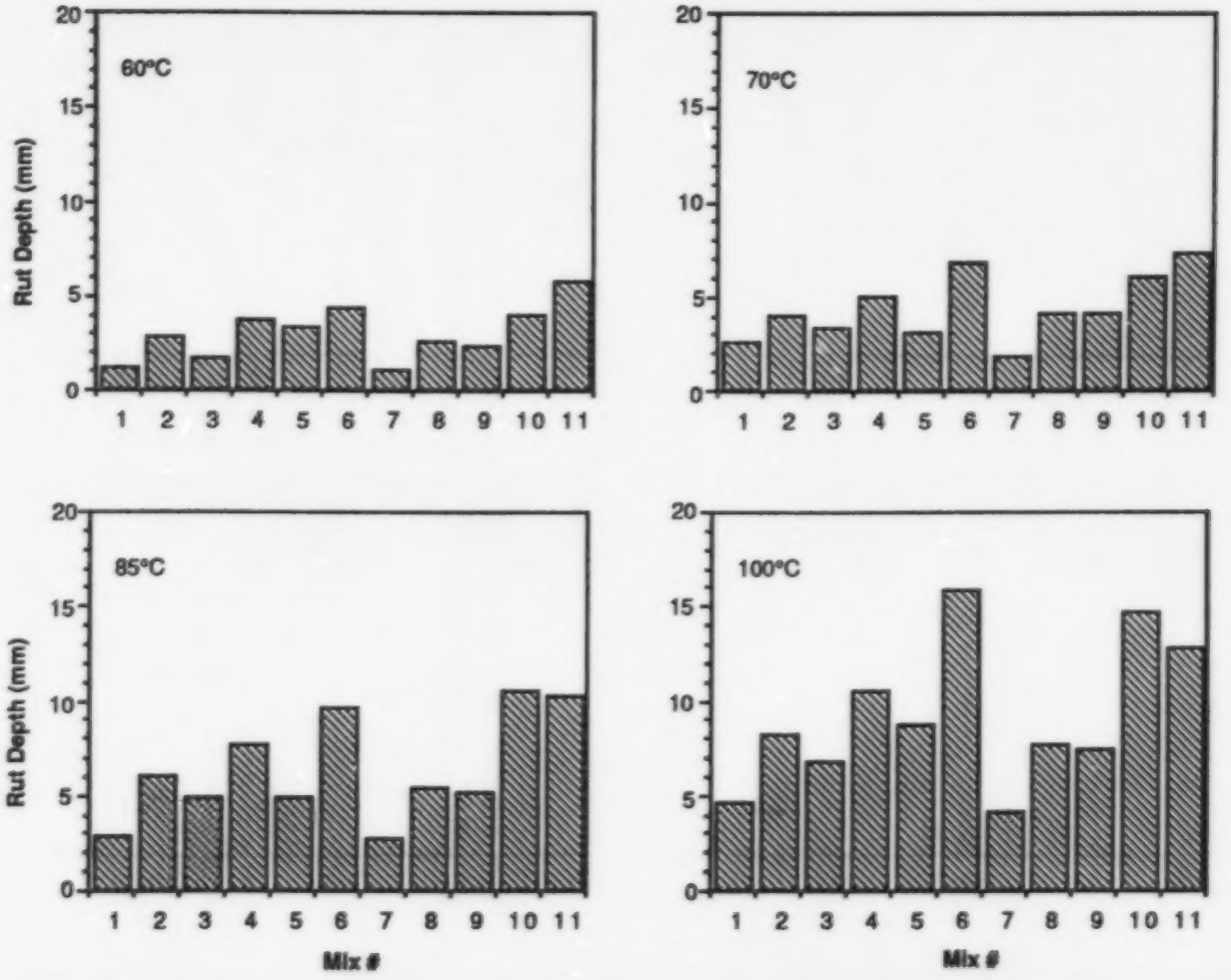


Fig. 16e Variation in Rut Depth at Different Initial Temperatures after 8000 Passes

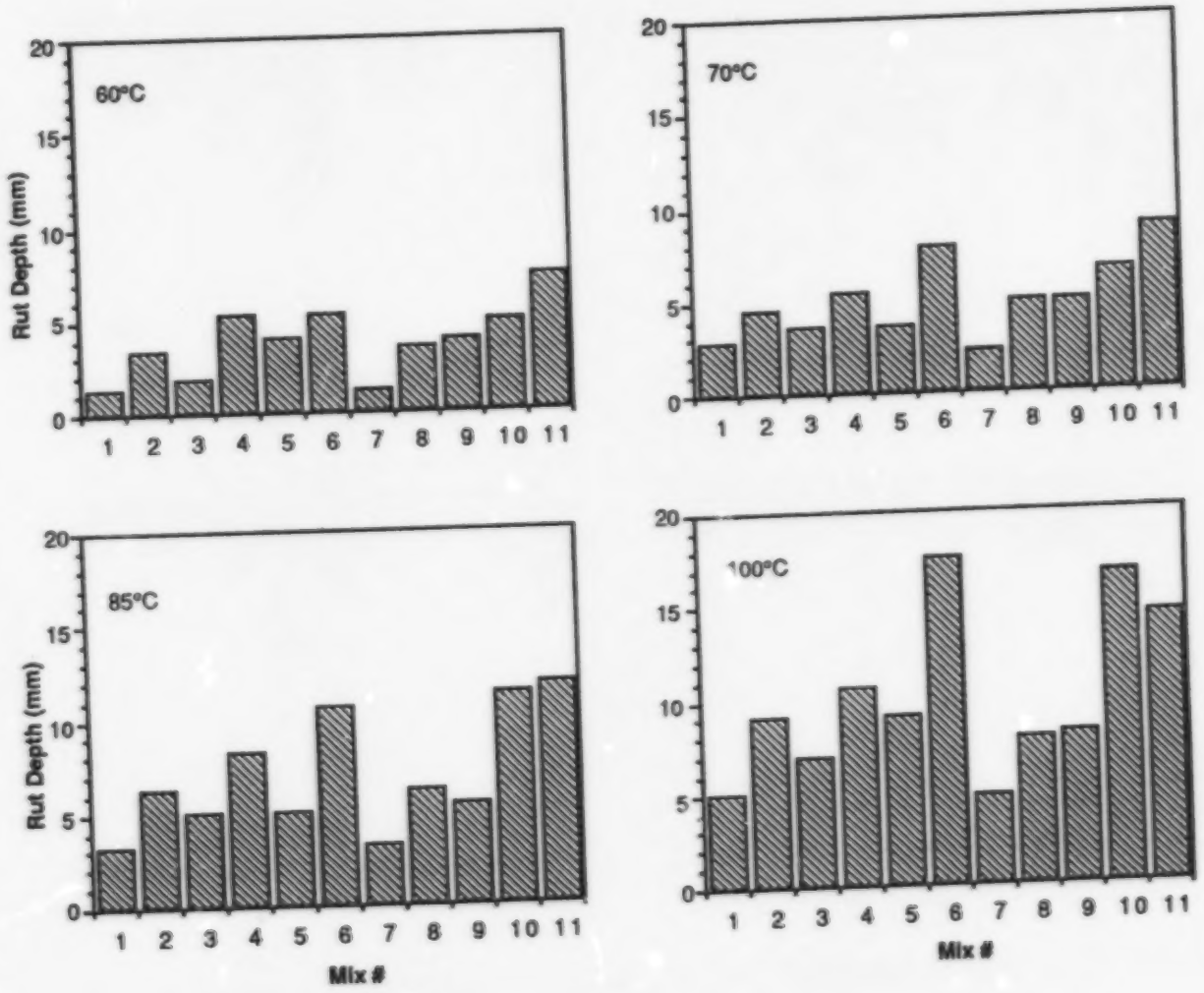


**Fig. 17 Effect of Different Binders on Mix 'Stiffness' at Different Temperatures**

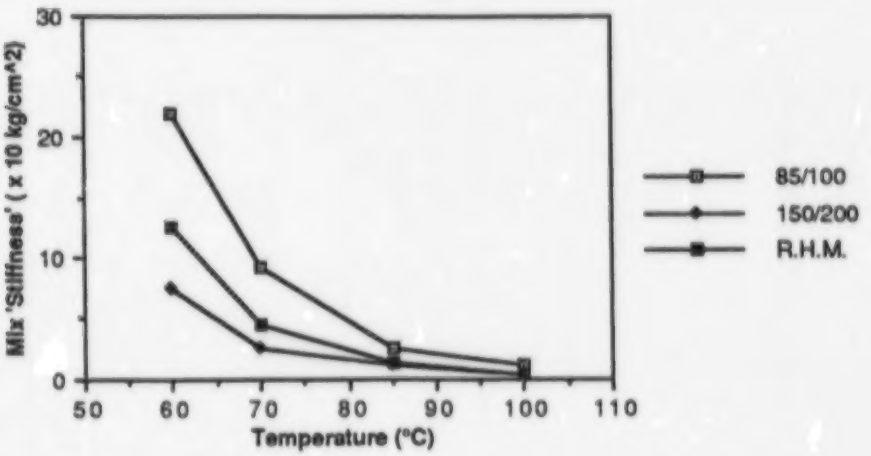



**Fig. 18 Percentage of Rutting Relative to 500 Passes with 100°C Initial Temperature Using Different Asphalt Cements**

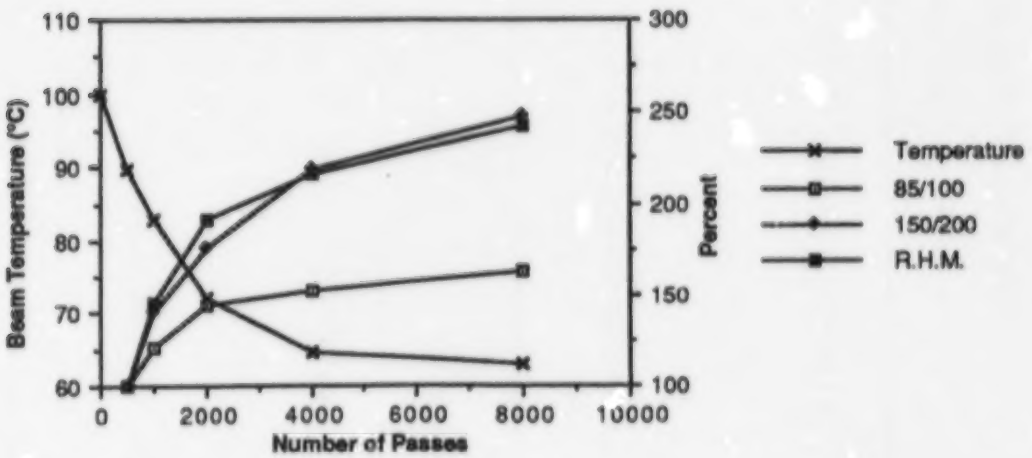
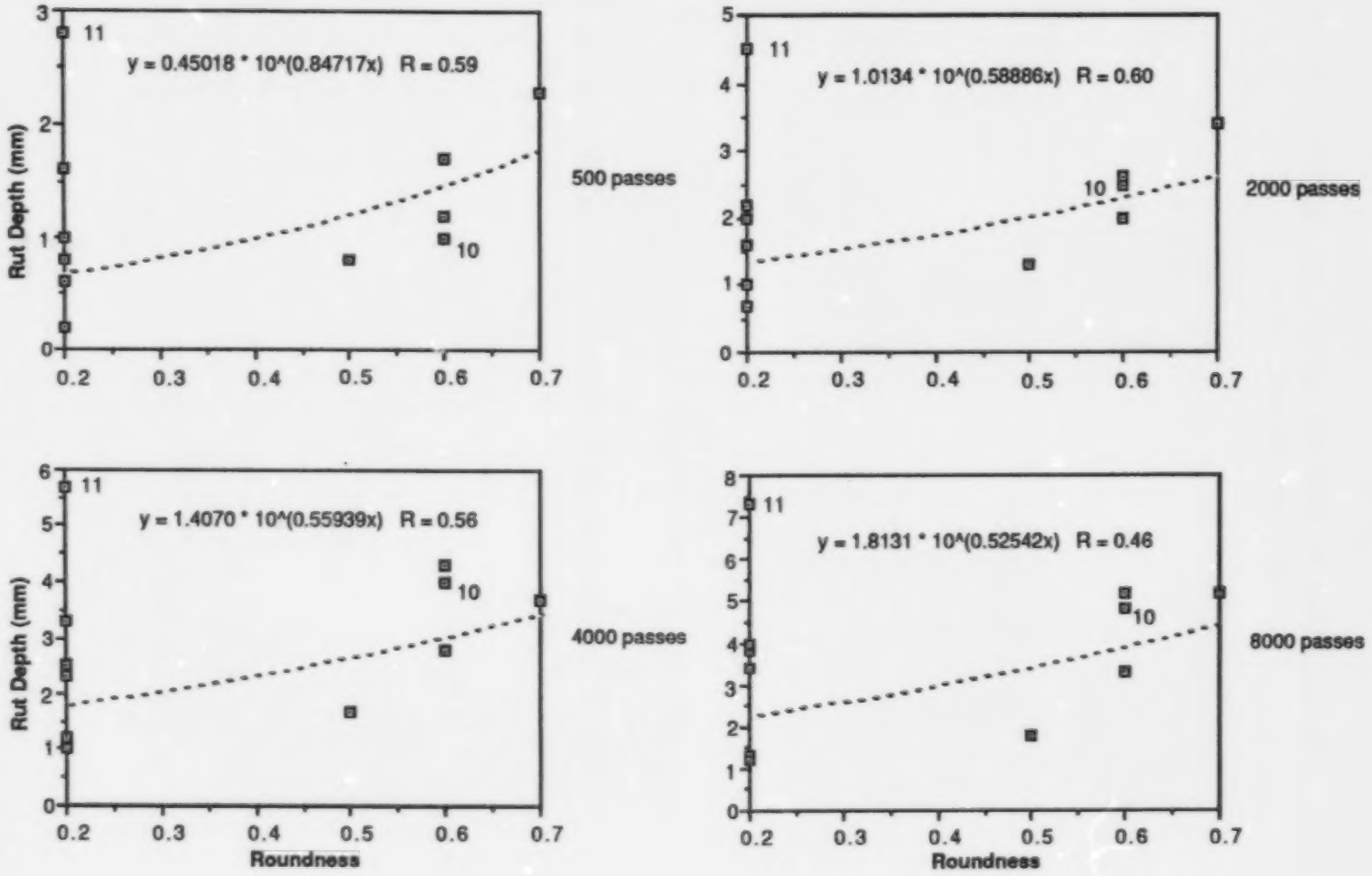
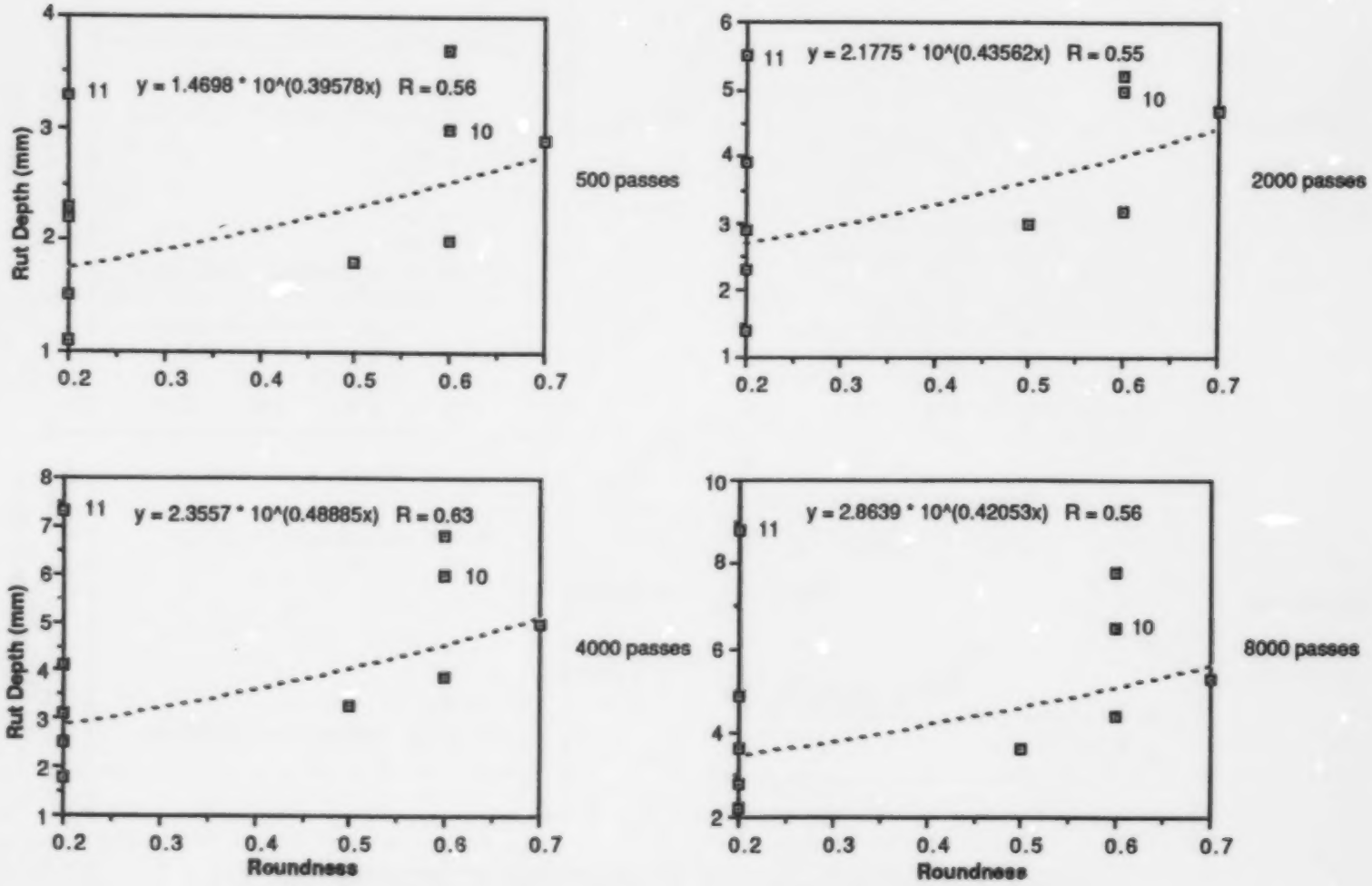


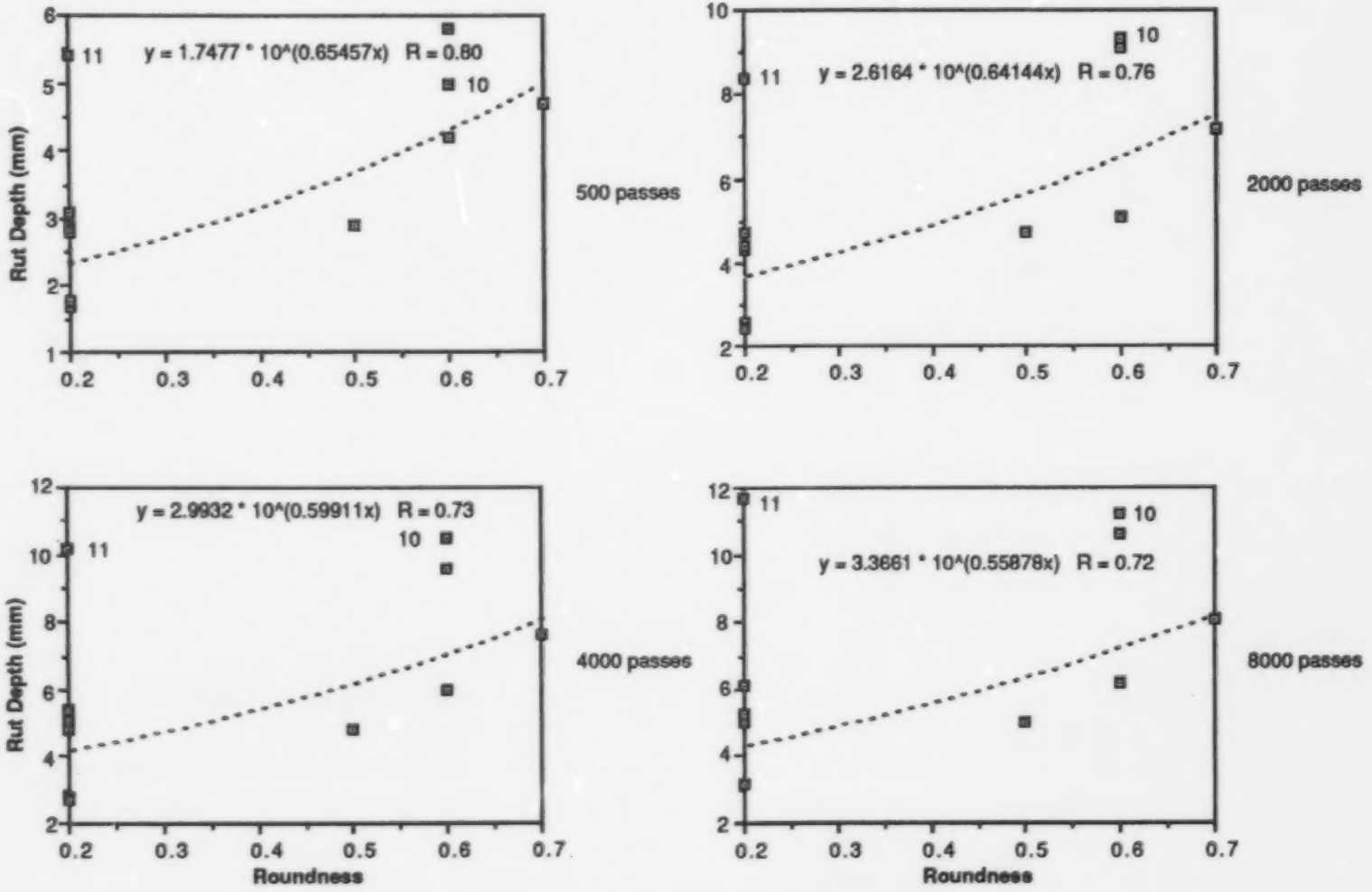
**Fig. 19a Variation of Rut Depth at 60°C with Roundness Values**



## Fig. 19b Variation of Rut Depth at 70°C with Roundness Values



## Fig. 19c Variation of Rut Depth at 85°C with Roundness Values



## Fig. 19d Variation of Rut Depth at 100°C with Roundness Values

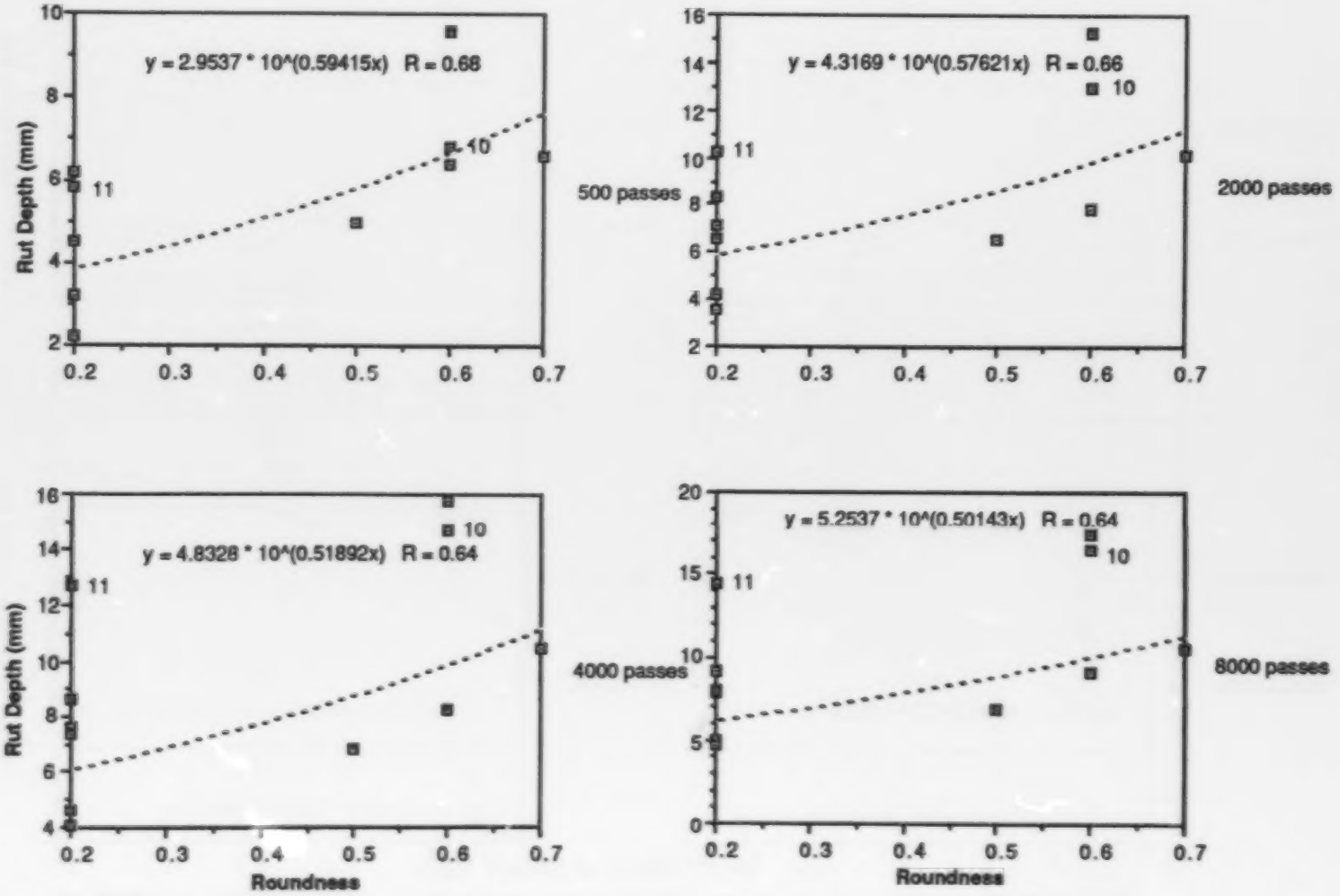


**Fig. 20a Variation of Rut Depth with Roundness at 60°C for Coarse Aggregates with Identical Sphericities**

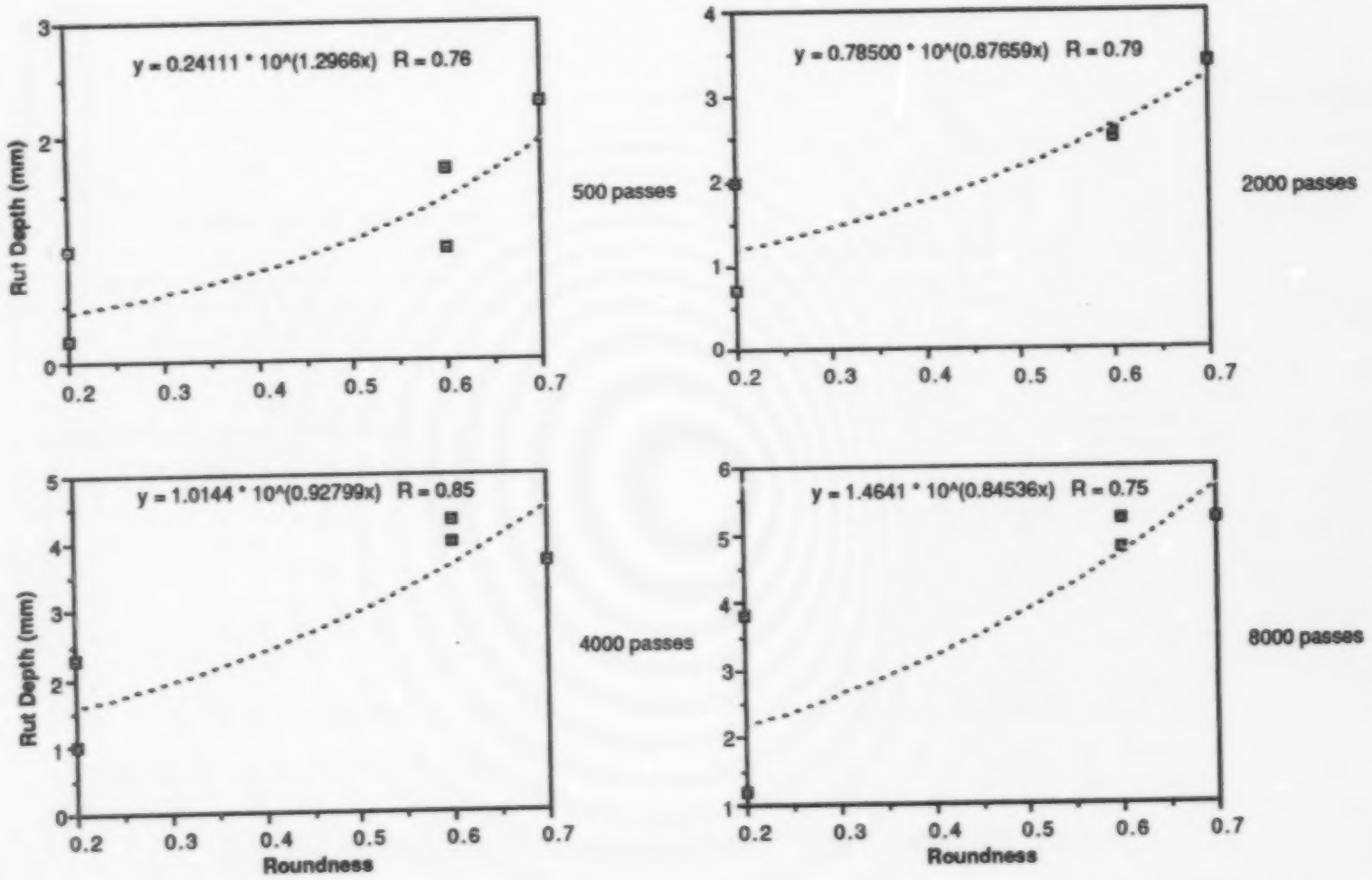


**Fig. 20b Variation of Rut Depth with Roundness at 70°C for Coarse Aggregates with Identical Sphericities**

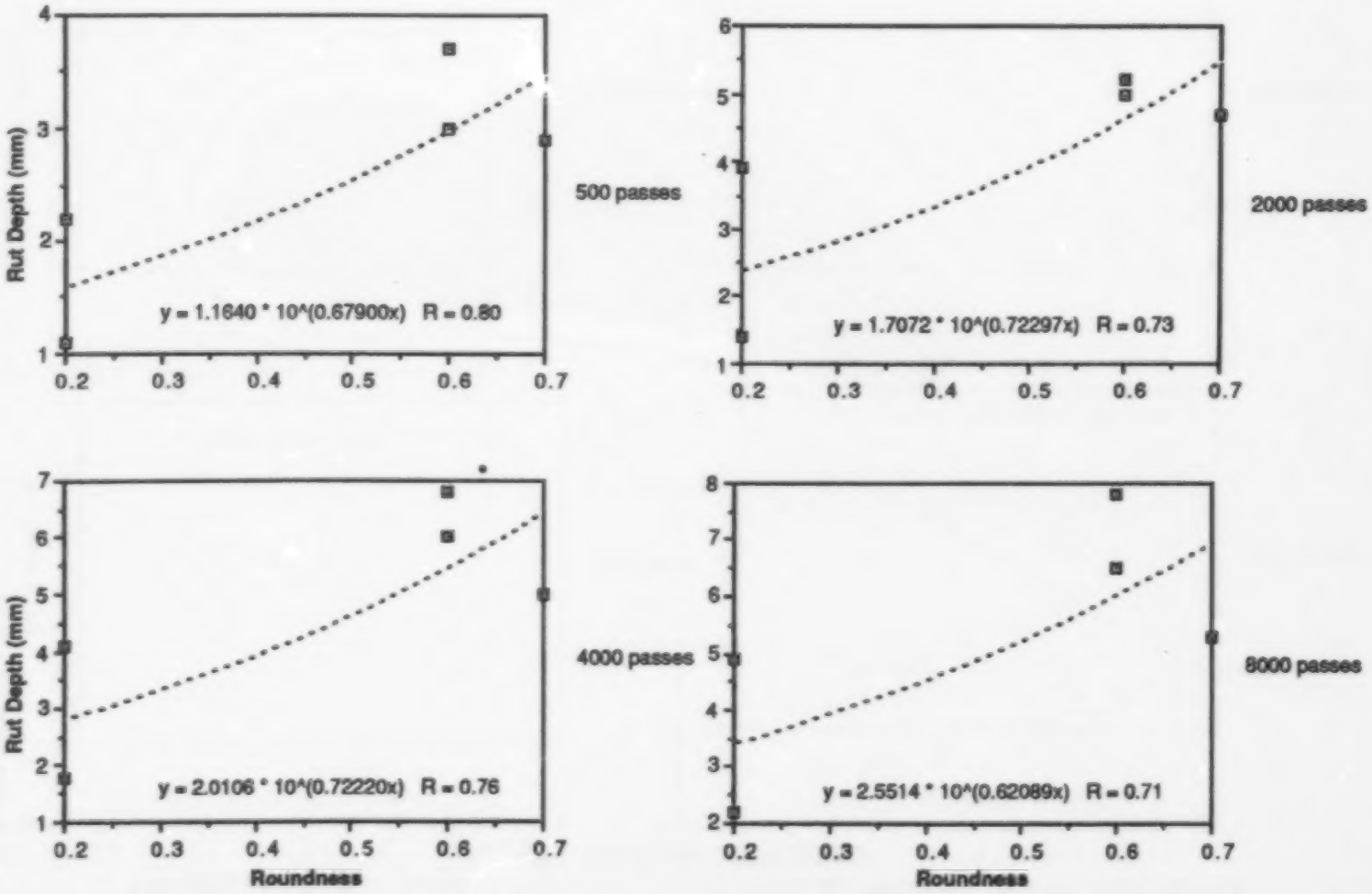


**Fig. 20c Variation of Rut Depth with Roundness at 85°C for Coarse Aggregates with Identical Sphericities**

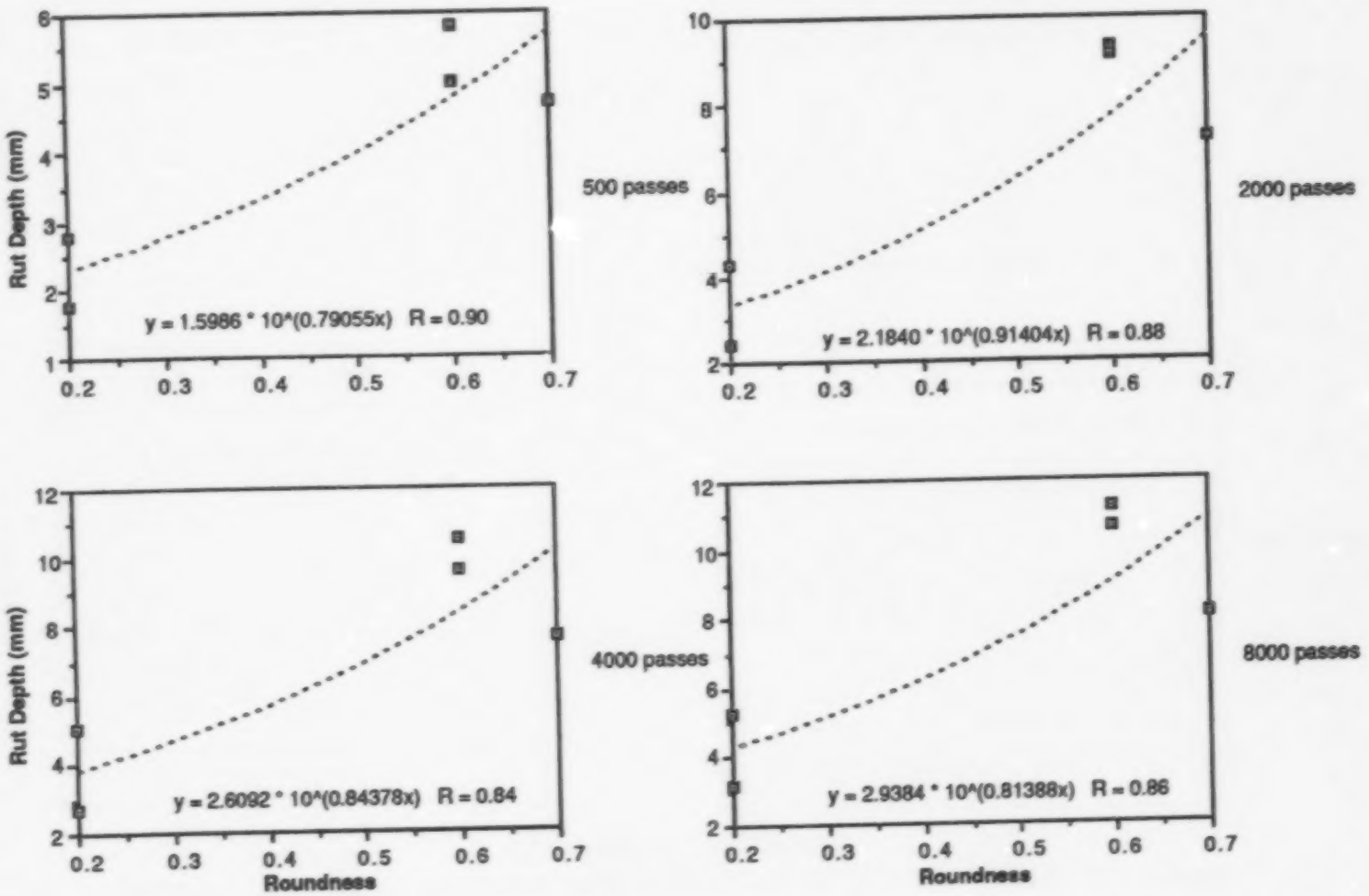


**Fig. 20d Variation of Rut Depth with Roundness at 100° for Coarse Aggregates with Identical Sphericities**

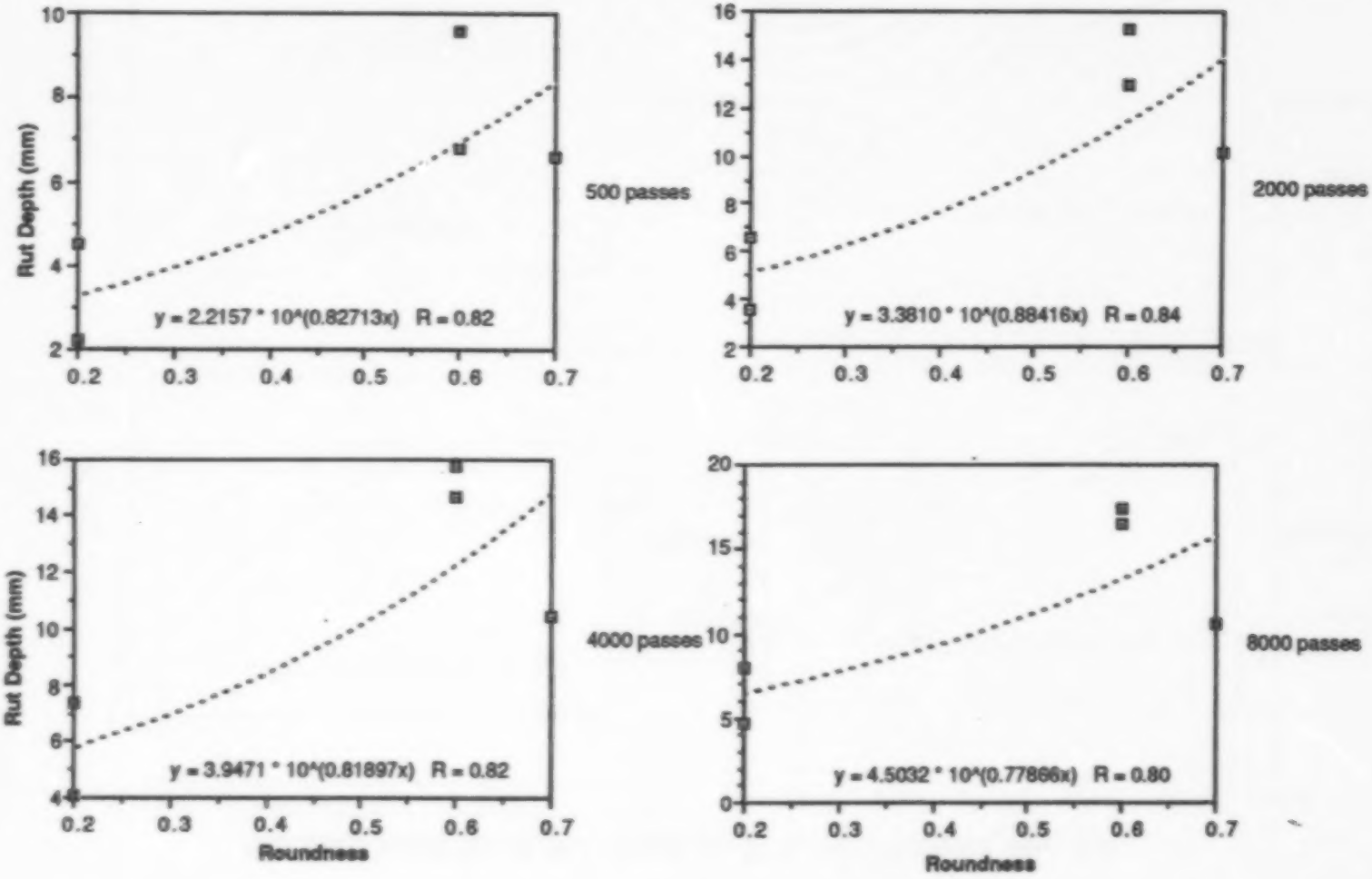
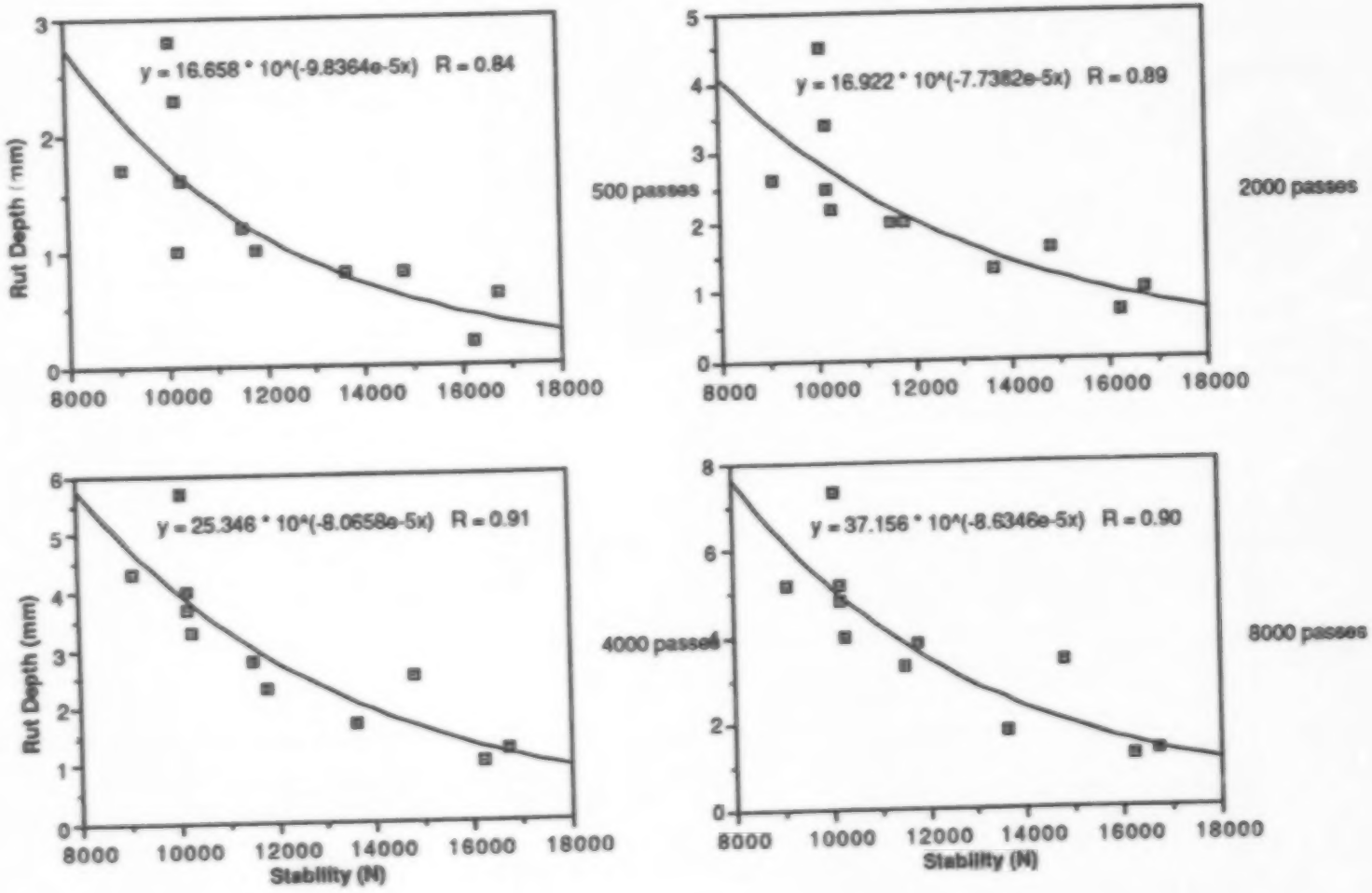


**Fig. 21a Variation of Rut Depth at 60°C with Marshall Stability**



## Fig. 21b Variation of Rut Depth at 70°C with Marshall Stability

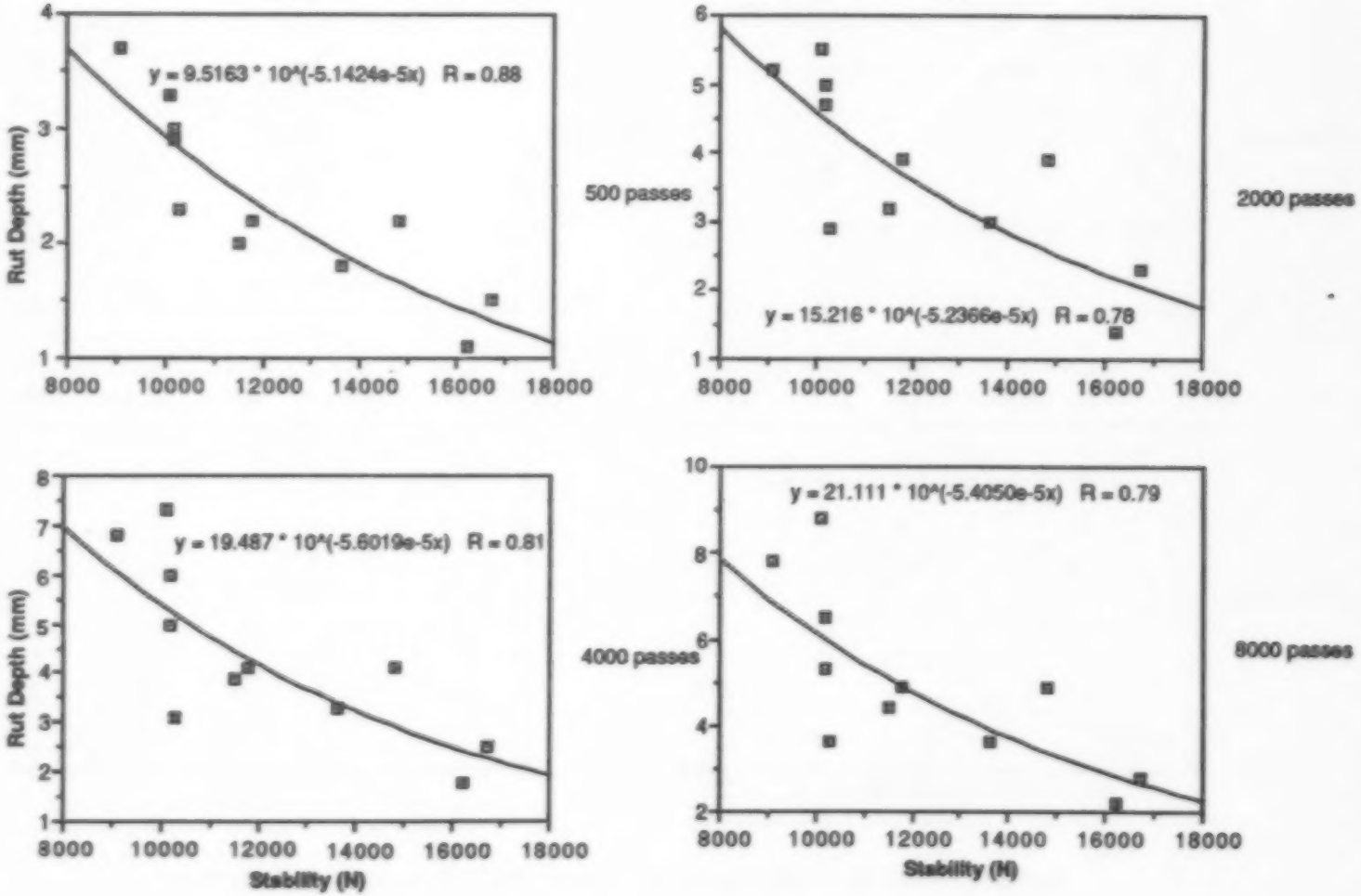
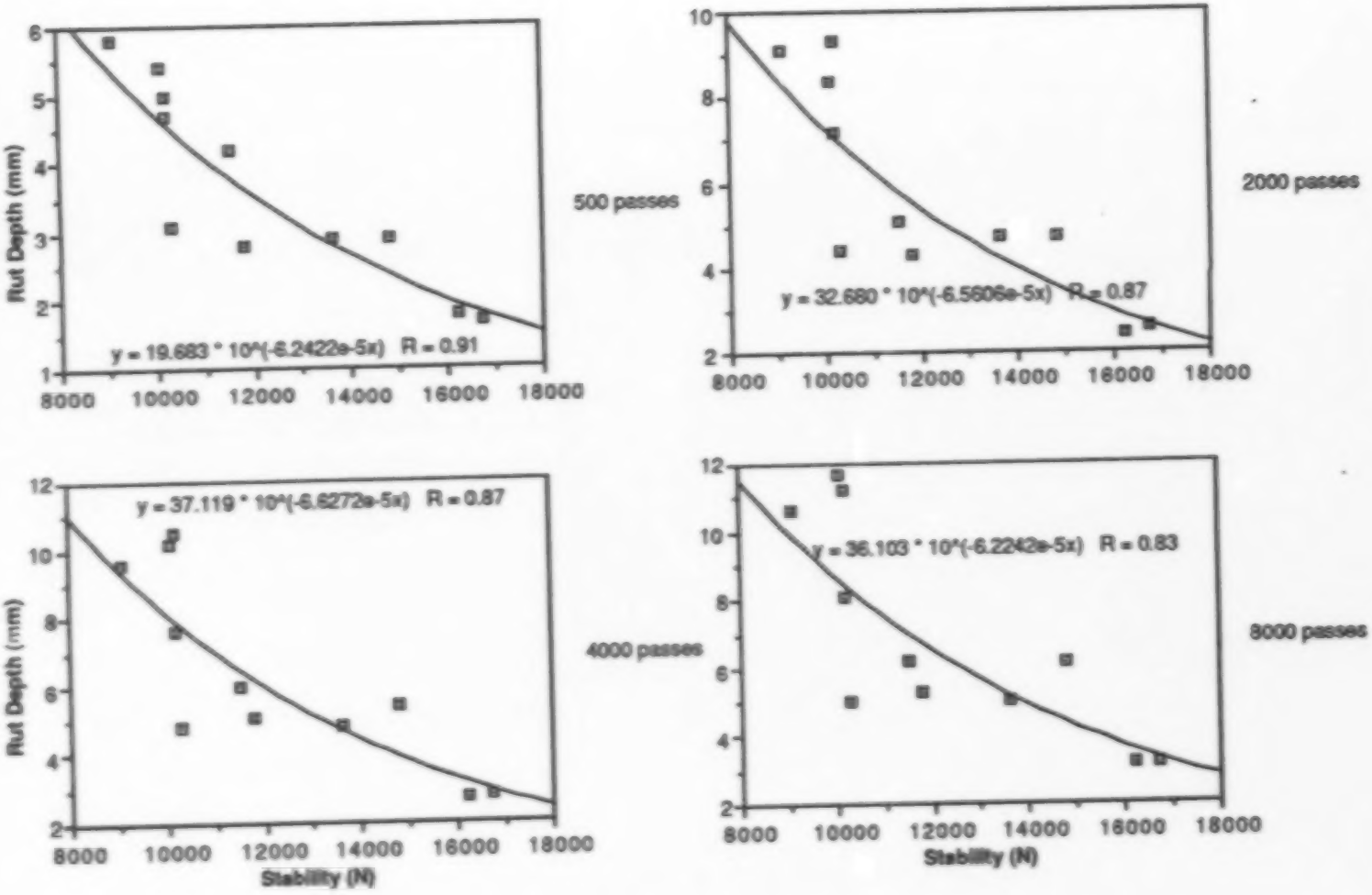


**Fig. 21c Variation of Rut Depth at 85°C with Marshall Stability**



## Fig. 21d Variation of Rut Depth at 100°C with Marshall Stability

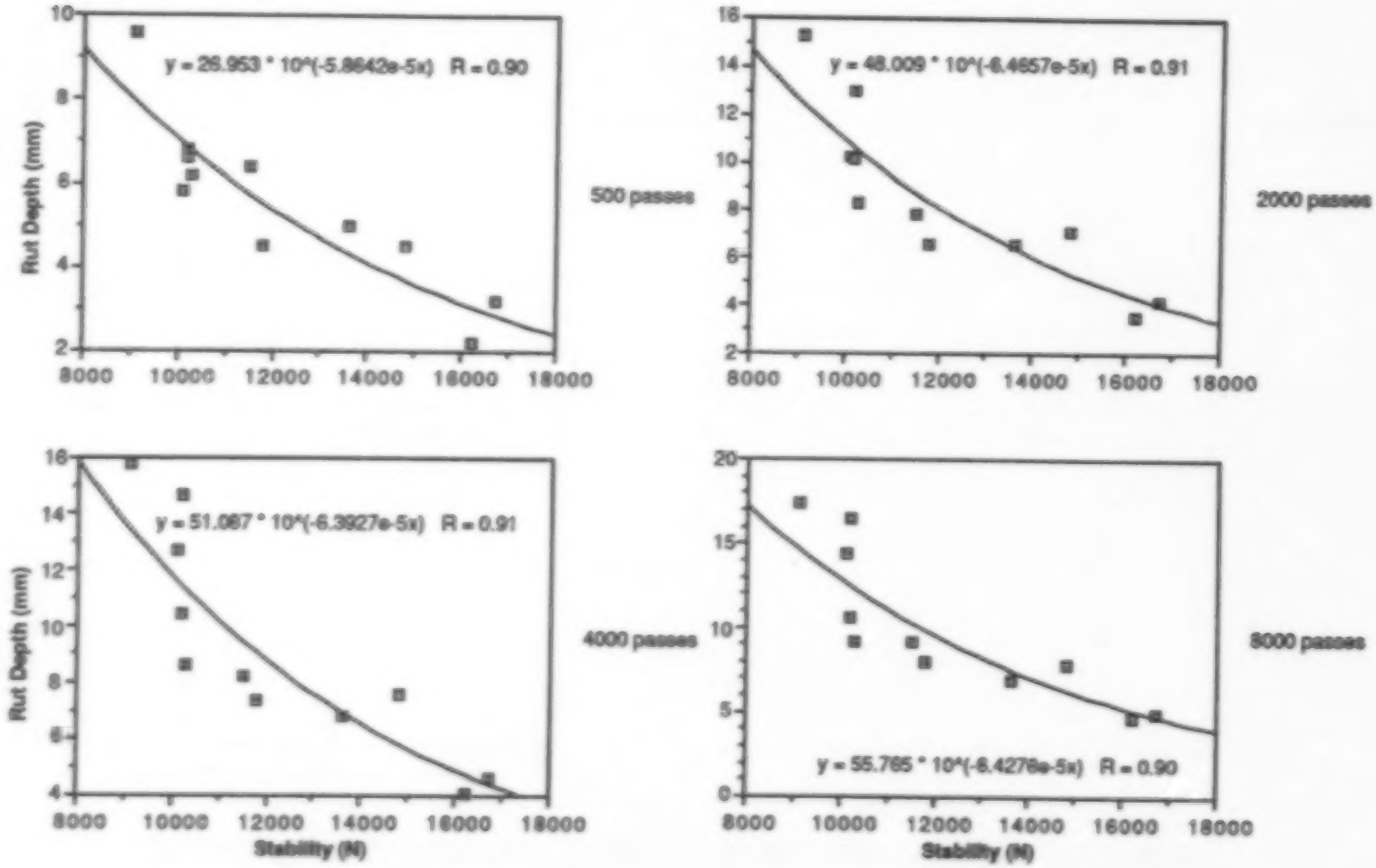


Fig. 22a Effect of Initial Void Content of Beam Samples on Rut Depth at 60°C

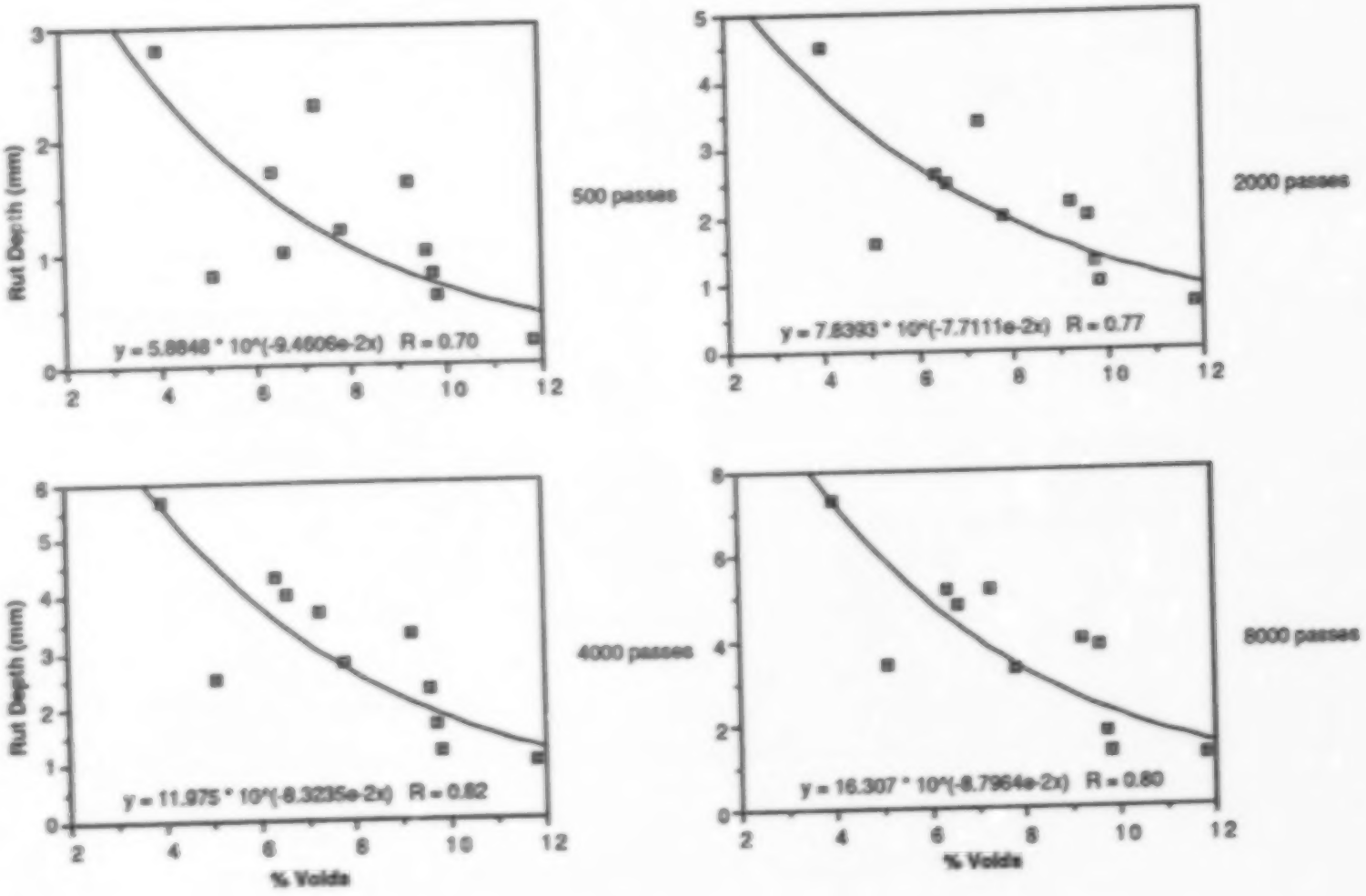


Fig. 22b Effect of Initial Void Content of Beam Samples on Rut Depth at 70°C

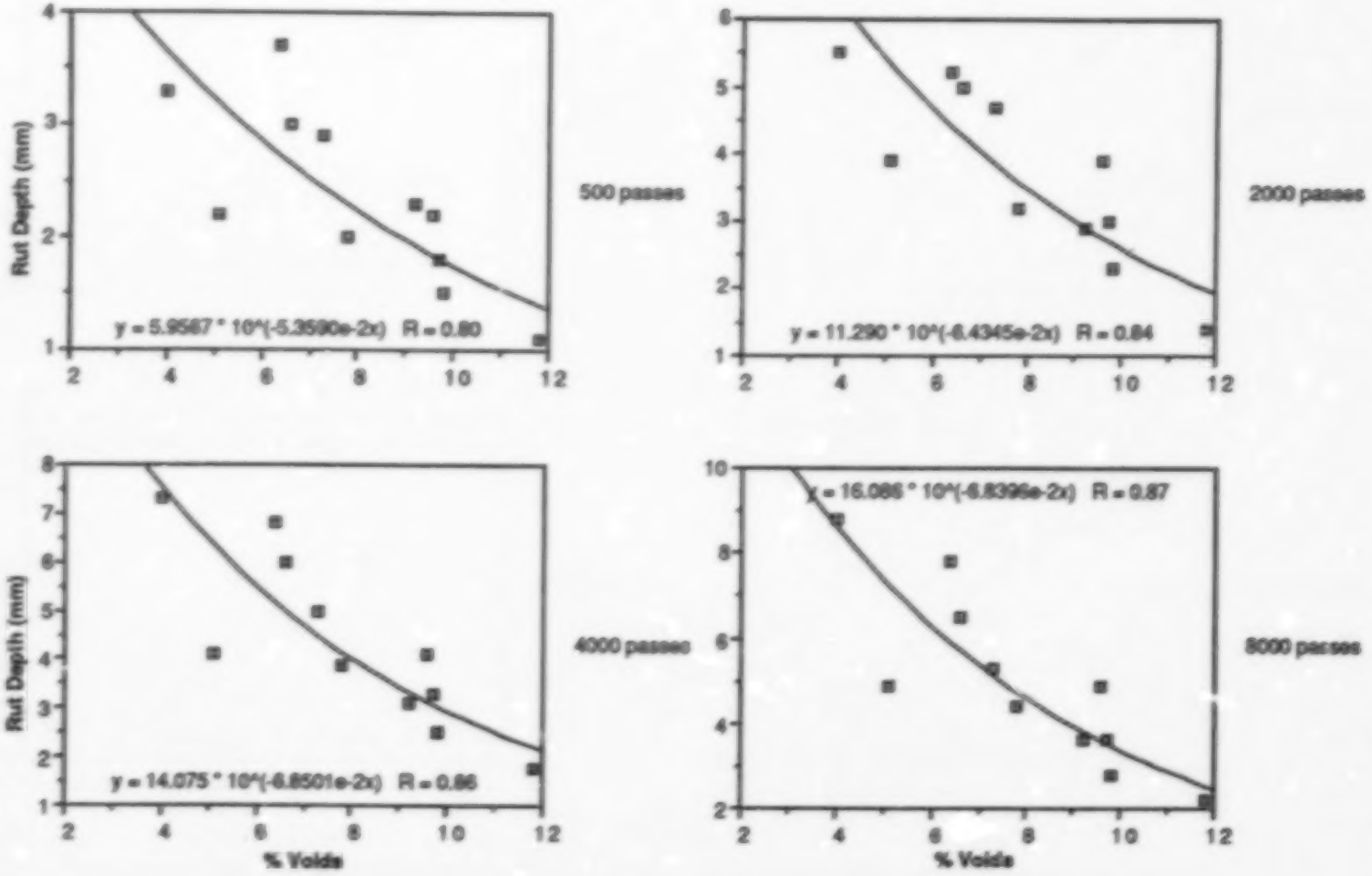
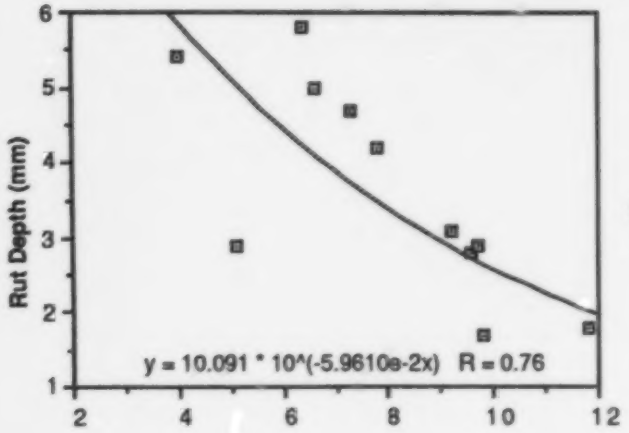
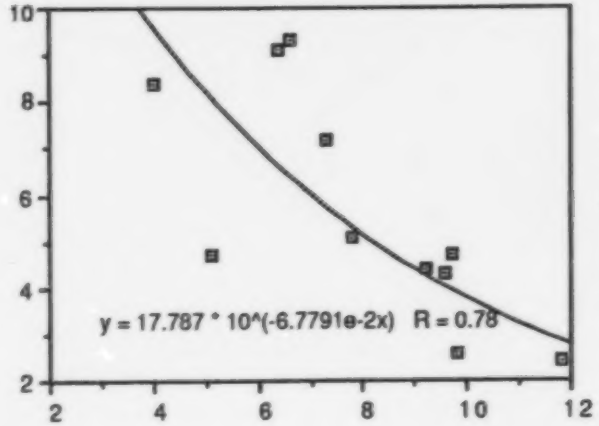


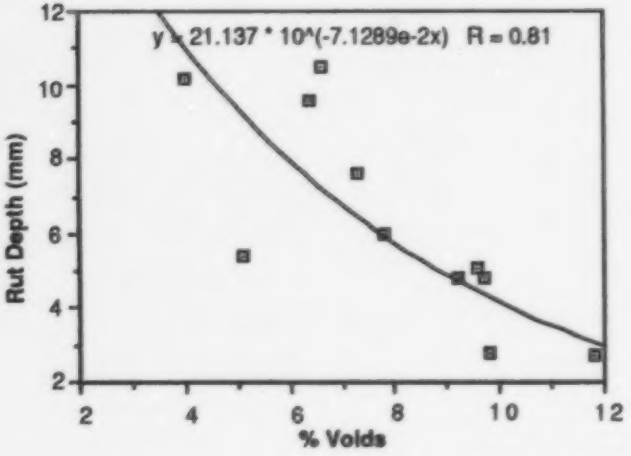
**Fig. 22c Effect of Initial Void Content of Beam Samples on Rut Depth at 85°C**



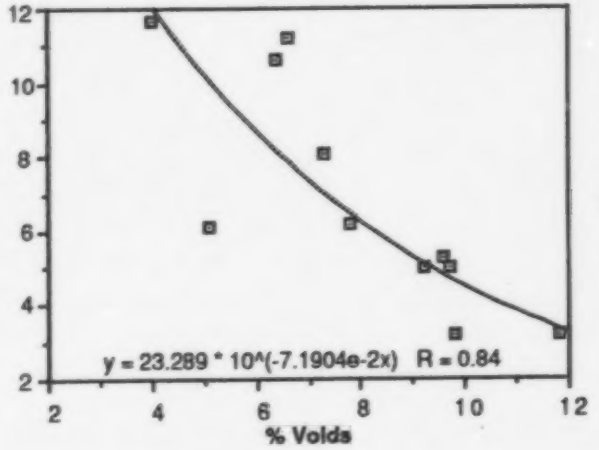

500 passes




2000 passes




4000 passes




8000 passes

## Fig. 22d Effect of Initial Void Content of Beam Samples on Rut Depth at 100°C

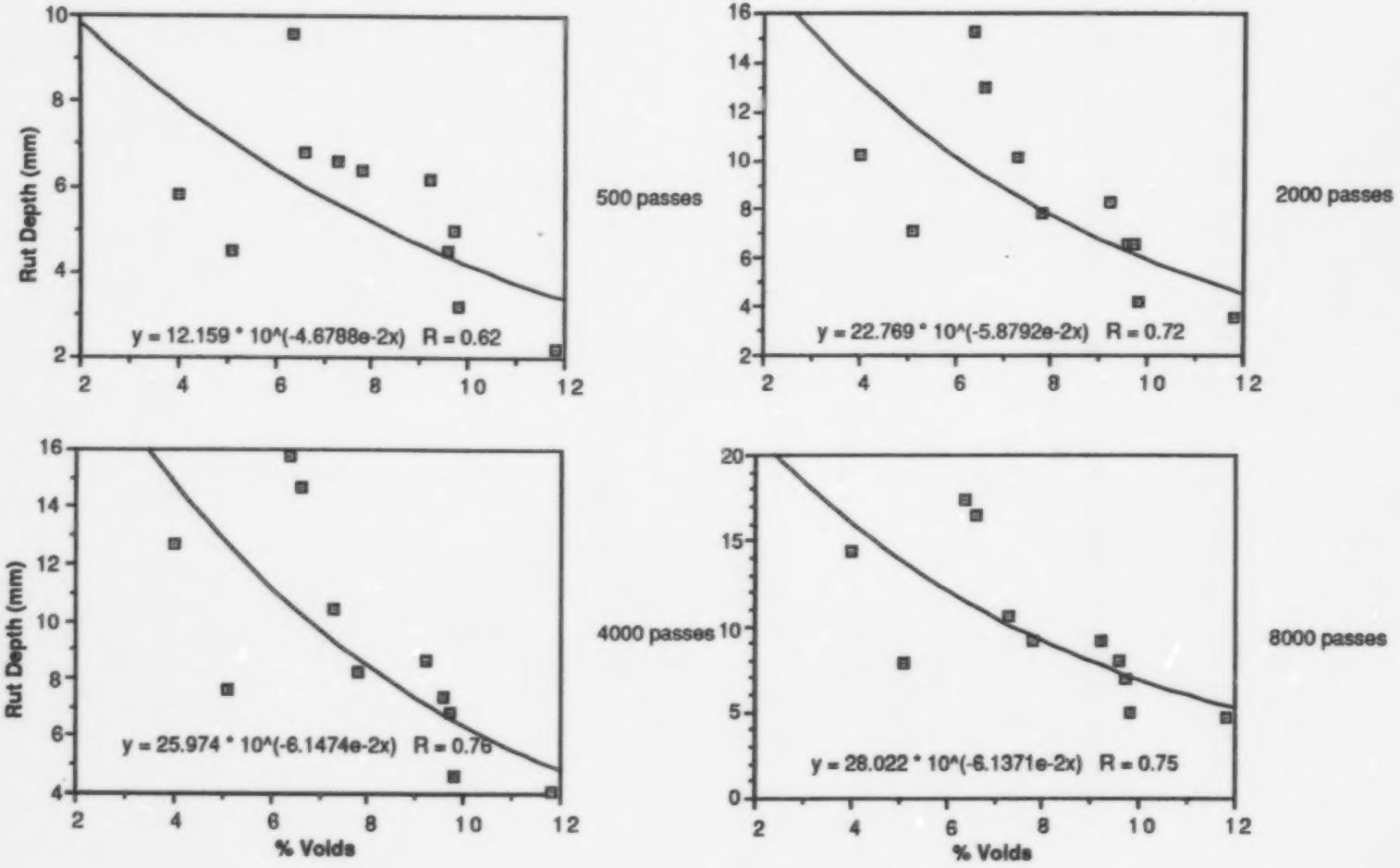
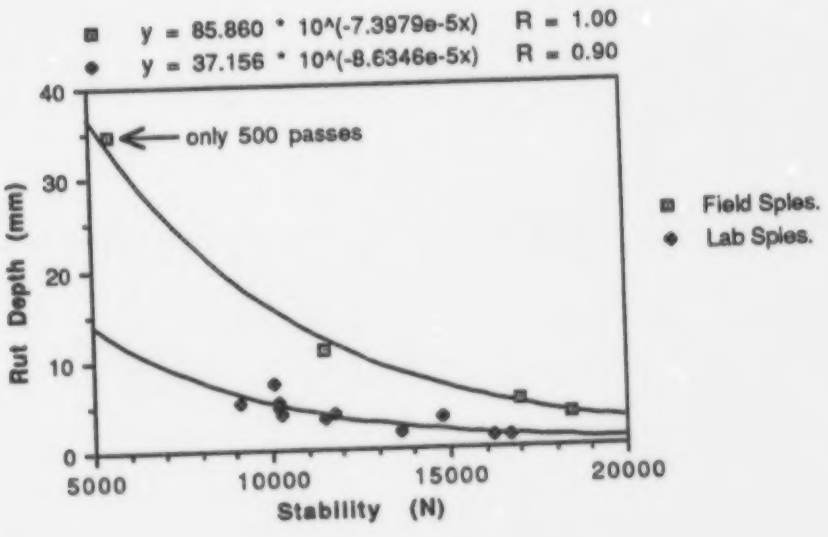


**Fig. 23 Comparison of Field and Laboratory Specimen Rutting at 60°C with Stability**



# APPENDIX A

## METHOD OF ROUNDNESS SPHERICITY AGGREGATE ANALYSIS

Small samples of coarse aggregate appoximately 300 grams in weight were examined and particle shapes compared to the silhouettes given in the Roundness Sphericity Comparison Chart. An average value for all of the particles within the sample was estimated. An initial estimate of fine aggregate values was determined by examining a small portion of sands and screenings samples.

The fine aggregate samples were further separated into six size fractions for a more detailed study. Each of the sizes was evaluated visually for overall roundness and sphericity. The results were tabulated and a weighted average for each of the values was then determined. Note that only some of the samples had been analyzed for size distribution.

## APPENDIX B

### WEIGHT RESTRICTION BY WIDTH OF TIRES

(a) Vehicles equipped with tires of less than 150 mm in width shall not be operated on a highway where the weight upon any millimetre in the width of the tire exceeds 9 kg.

or

(b) Vehicles equipped with tires of 150 mm or more in width shall not be operated on a highway where the weight upon any millimetre in the width exceeds 11 kg.

Example:

Tire size 11.00 x 22
Tire tread width = 11 inches
11 inches = 279.4 mm
279.4 mm x 11 kg = 3073.4 kg
Maximum weight on tire = 3073.4 kg